1979

Roll control of submarines

Artunc, Izzet

Monterey, California. Naval Postgraduate School

ROLL CONTROL OF SUBMARINES

Izzet Artunc

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

ROLL CONTROL OF SUBMARINES

by

Izzet Artunc

December 1979

Thesis Advisor: G.J. Thaler

Approved For Public Release; Distribution Unlimited.

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Roll Control Of Submarines		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis December 1979
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Izzet Artunc		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE December 1979
		13. NUMBER OF PAGES 194
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Depth Pitch Roll Control Of Submarines

Differentially Deflected Fairwater Planes

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The use of differentially deflected fairwater planes to control submarine rolling is studied. Because of coupling between pitch and roll angles, the snap roll that occurs in a high speed hard turn affects the stability of a submarine not only in the horizontal plane but also in the vertical plane. Direct roll control was achieved by making use of the fairwater planes in a differentially deflected mode such that they could give counter

moment to reduce the snap roll. A roll controller was designed as a position and velocity feedback controller. Controlled roll angle improved the depth and pitch stability of submarine.

Approved For Public Release; Distribution Unlimited.

Roll Control Of Submarines

by

Izzet Artunc
Lieutenant, Turkish Navy
B.S.E.E., Naval Postgraduate School, 1979

Submitted In Partial Fulfillment Of The
Requirements For The Degree Of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

From The

NAVAL POSTGRADUATE SCHOOL
December 1979

ABSTRACT

The use of differentially deflected fairwater planes to control submarine rolling is studied. Because of coupling between pitch and roll angles, the snap roll that occurs in a high speed hard turn affects the stability of a submarine not only in the horizontal plane but also in the vertical plane. Direct roll control was achieved by making use of the fairwater planes in a differentially deflected mode such that they could give counter moment to reduce the snap roll. A roll controller was designed as a position and velocity feedback controller. Controlled roll angle improved the depth and pitch stability of submarine.

TABLE OF CONTENTS

LIST OF FIGURES -- 6

ACKNOWLEDGEMENT -- 14

I. INTRODUCTION -- 15

II. NATURE OF THE PROBLEM -- 17

III. DIGITAL COMPUTER SIMULATION OF SUBMARINE MOTION --- 26

IV. AUTOMATIC DEPTH AND PITCH CONTROL -- 48

A. OPTIMAL SOLUTION TO THE LINEARIZED SUBMARINE EQUATIONS -- 48

B. AUTOMATIC DEPTH-PITCH CONTROLLER AND SIMULATION OF THE RESULT -- 65

V. AUTOMATIC ROLL CONTROLLER -- 88

A. ESTIMATING ROLL MOMENT DUE TO DIFFERENTIALLY DEFLECTED SAILPLANES -- 90

B. ROLL CONTROLLER DESIGN -- 93

1. Proportional Controller -- 96

2. Compensation Of The System With Velocity Feedback -- 106

C. ROLL CONTROLLER STABILITY TESTS -- 152

VI. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK -- 169

A. DISCUSSION AND CONCLUSION -- 169

B. RECOMMENDATIONS FOR FURTHER WORK -- 172

APPENDIX A: NOTATION AND EQUATIONS OF MOTION -- 174

APPENDIX B: COMPUTER PROGRAM FOR ROLL CONTROL SIMULATION -- 186

LIST OF REFERENCES -- 193

INITIAL DISTRIBUTION LIST -- 194

LIST OF FIGURES

Page

1. Hydrodynamic Forces In A Turn 20
2. Coordinate System 21
3. Depth vs. Time. With No Controller. UCK = 24 Knots Rudder Ordered = 35^{o} 22
4. Pitch vs. Time. With No Controller. UCK = 24 Knots Rudder Ordered = 35^{o} 23
5. Roll vs. Time. With No Controller. UCK = 24 Knots Rudder Ordered = 35^{o} 24
6. Rudder Response vs. Time. With No Controller. UCK = 24 Knots. Rudder Ordered = 35^{o} 25
7. Rudder Hydraulic Actuator Model 29
8. Depth vs. Time. With No Controller. UCK = 18 Knots Rudder Ordered = 35^{o} 30
9. Pitch vs. Time. With No Controller. UCK = 18 Knots Rudder Ordered = 35^{o} 31
10. Roll vs. Time. With No Controller. UCK = 18 Knots Rudder Ordered = 35^{o} 32
11. Speed Change vs. Time. With No Controller. UCK = 18 Knots. Rudder Ordered = 35^{o} 33
12. Yaw vs. Time. With No Controller. UCK = 18 Knots Rudder Ordered = 35^{o} 34
13. Rudder Response vs. Time. With No Controller. UCK = 18 Knots. Rudder Ordered = 35^{o} 35
14. Depth vs. Time. With No Controller. UCK = 12 Knots Rudder Ordered = 35^{o} 36
15. Pitch vs. Time. With No Controller. UCK = 12 Knots Rudder ordered = 35^{o} 37
16. Roll vs. Time. With No Controller. UCK = 12 Knots Rudder Ordered = 35^{o} 38
17. Speed Change vs. Time. With No Controller. UCK = 12 Knots. Rudder Ordered = 35^{o} 39

Page

18. Yaw vs. Time. With No Controller. UCK = 12 Knots Rudder Ordered = 35^{o} 40

19. Rudder Response vs. Time. With No Controller. UCK = 12 Knots. Rudder Ordered = 35^{o} 41

20. Depth vs. Time. With No Controller. UCK = 6 Knots. Rudder Ordered = 35^{o} 42

21. Pitch vs. Time. With No Controller. UCK = 6 Knots. Rudder Ordered = 35^{o} 43

22. Roll vs. Time. With No Controller. UCK = 6 Knots. Rudder Ordered = 35^{o} 44

23. Speed Change vs. Time. With No Controller. UCK = 6 Knots. Rudder Ordered = 35^{o} 45

24. Yaw vs. Time. With No Controller. UCK = 6 Knots. Rudder Ordered = 35^{o} 46

25. Rudder Response vs. Time. With No Controller. UCK = 6 Knots. Rudder Ordered = 35^{o} 47

26. Linear Regulator Block Diagram. 50

27. K11 vs. Time 54

28. K12 vs. Time 55

29. K13 vs. Time 56

30. K14 vs. Time 57

31. K22 vs. Time 58

32. K23 vs. Time 59

33. K24 vs. Time 60

34. K33 vs. Time 61

35. K34 vs. Time 62

36. K44 vs. Time 63

37. K11 vs. Time. With Transformation Of Depth Rate = W 64

38. Depth And Pitch Controller Block Diagram 66

39. Hydraulic Actuator Model For Stern And Fairwater Plane 67

40. Depth vs. Time. With Depth-Pitch Controller. UCK = 6 Knots. Rudder Ordered = 35^{o} 72

Page

41. Pitch vs. Time. With Depth-Pitch Controller. UCK = 6 Knots. Rudder Ordered = 35^{o} 73

42. Roll vs. Time. With Depth-Pitch Controller. UCK = 6 Knots. Rudder Ordered = 35^{o} 74

43. Sternplane Angle vs. Time. With Depth-Pitch Controller. UCK = 6 Knots. Rudder Ordered = 35^{o} 75

44. Depth vs. Time. With Depth-Pitch Controller. UCK = 12 Knots. Rudder Ordered = 35^{o} 76

45. Pitch vs. Time. With Depth-Pitch Controller. UCK = 12 Knots. Rudder Ordered = 35^{o} 77

46. Roll vs. Time. With Depth-Pitch Controller. UCK = 12 Knots. Rudder Ordered = 35^{o} 78

47. Sternplane Angle vs. Time. With Depth-Pitch Controller. UCK = 12 Knots. Rudder Ordered = 35^{o} 79

48. Depth vs. Time. With Depth-Pitch Controller. UCK = 18 Knots. Rudder Ordered = 35^{o} 80

49. Pitch vs. Time. With Depth-Pitch Controller. UCK = 18 Knots. Rudder Ordered = 35^{o} 81

50. Roll vs. Time. With Depth-Pitch Controller. UCK = 18 Knots. Rudder Ordered = 35^{o} 82

51. Sternplane Angle vs. Time. With Depth-Pitch Controller. UCK = 18 Knots. Rudder Ordered = 35^{o} 83

52. Depth vs. Time. With Depth-Pitch Controller. UCK = 24 Knots. Rudder Ordered = 35^{o} 84

53. Pitch vs. Time. With Depth-Pitch Controller. UCK = 24 Knots. Rudder Ordered = 35^{o} 85

54. Roll vs. Time. With Depth-Pitch Controller. UCK = 24 Knots. Rudder Ordered = 35^{o} 86

55. Sternplane Angle vs. Time. With Depth-Pitch Controller. UCK = 24 Knots. Rudder Ordered = 35^{o} 87

56. Definition Of Positive Direction Of Differentially Deflected Sailplanes 92

57.1. Basic Position Feedback Control Scheme 95
.2. Basic Position And Velocity Feedback Control Scheme

58. Depth vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35^{o}. Initial Roll Angle = 0^{o} 98

Page

59. Pitch vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 99

60. Roll vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 100

61. Sternplane Angle vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 101

62. Sailplane Angle vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 102

63. Depth vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = -5° 103

64. Pitch vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = -5° 104

65. Roll vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = -5° 105

66. Roll vs. Time. K1 = 3. K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = -20° 108

67.1. Roll vs. Time. K1 = 3. K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20° 110
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

68.1. Pitch vs. Time. K1 = 3. K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20° 111
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

69.1. Roll vs. Time. K1 = 3. K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20° 112
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

70.1. Sternplane Angle vs. Time. K1 = 3. K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20° 113
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

71.1. Sailplane Angle vs. Time. K1 = 3. K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20° 114
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

72. Complete Depth-Pitch-Roll Control Block Diagram 116

73.1. Depth vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20° 117
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

Page

74.1. Pitch vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20° 118
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

75.1. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20° 119
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

76.1. Sternplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20° 120
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

77.1. Sailplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20° 121
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

78.1. Depth vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 18 Knots. Initial Roll Angle = -20° 122
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

79.1. Pitch vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 18 Knots. Initial Roll Angle = -20° 123
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

80.1. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 18 Knots. Initial Roll Angle = -20° 124
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

81.1. Sternplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 18 Knots. Initial Roll Angle = -20° 125
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

82.1. Sailplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 18 Knots. Initial Roll Angle = -20° 126
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

83.1. Depth vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 12 Knots. Initial Roll Angle = -20° 127
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

84.1. Pitch vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 12 Knots. Initial Roll Angle = -20° 128

Page

.2. Rudder Response vs. Time (Rudder Ordered = 35°)

85.1. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 12 Knots. Initial Roll Angle = -20° 129
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

86.1. Sternplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 12 Knots. Initial Roll Angle = -20° 130
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

87.1. Sailplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 12 Knots. Initial Roll Angle = -20^{0} 131
.2. Rudder Response vs. Time (Rudder Ordered = 35°)

88. Depth vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 132

89. Pitch vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 133

90. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 134

91. Sternplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 135

92. Sailplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 136

93. Depth vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 18 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 137

94. Pitch vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 18 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 138

95. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 18 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 139

96. Sternplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 18 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 140

Page

97. Sailplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 18 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 141

98. Depth vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 12 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 142

99. Pitch vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 12 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 143

100. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 12 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 144

101. Sternplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 12 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 145

102. Sailplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 12 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0° 146

103. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 24 Knots. Rudder Ordered =35°. Initial Roll Angle = -20° 147

104. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 18 Knots. Rudder Ordered = 35°. Initial Roll Angle = -20° 148

105. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3. K2 = 10. UCK = 12 Knots. Rudder Ordered = 35°. Initial Roll Angle = -20° 149

106.1. Depth vs. Time. Roll Stability Step Test. UCK = 24 Knots. Rudder Ordered = 35° 154
.2. Disturbance Moment vs. Time

107.1. Pitch vs. Time. Roll Stability Step Test. UCK = 24 Knots. Rudder Ordered = 35° 155
.2. Disturbance Moment vs. Time

108.1. Roll vs. Time. Roll Stability Step Test. UCK = 24 Knots. Rudder Ordered = 35° 156
.2. Distrubance Moment vs. Time

109.1. Sternplane Angle vs. Time. Roll Stability Step Test. UCK = 24 Knots. Rudder Ordered = 35° 157
.2. Disturbance Moment vs. Time

Page

110.1. Sailplane Angle vs. Time. Roll Stability Step Test. UCK = 24 Knots. Rudder Ordered = 35^{o} 158
.2. Distrubance Moment vs. Time

111.1. Depth vs. Time. Roll Stability Step Test. UCK = 18 Knots. Rudder Ordered = 35^{o} 159
.2. Disturbance Moment vs. Time

112.1. Pitch vs. Time. Roll Stability Step Test. UCK = 18 Knots. Rudder Ordered = 35^{o} 160
.2. Disturbance Moment vs. Time

113.1. Roll vs. Time. Roll Stability Step Test. UCK = 18 Knots. Rudder Ordered = 35^{o} 161
.2. Disturbance Moment vs. Time

114.1. Sternplane Angle vs. Time. Roll Stability Step Test. UCK = 18 Knots. Rudder Ordered = 35^{o} 162
.2. Distrubance Moment vs. Time

115.1. Sailplane Angle vs. Time. Roll Stability Step Test. UCK = 18 Knots. Rudder Ordered = 35^{o} 163
.2. Disturbance Moment vs. Time.

116.1. Depth vs. Time. Roll Stability Step Test. UCK = 12 Knots. Rudder Ordered = 35^{o} 164
.2. Disturbance Moment vs. Time

117.1. Pitch vs. Time. Roll Stability Step Test. UCK = 12 Knots. Rudder Ordered = 35^{o} 165
.2. Disturbance Moment vs. Time

118.1. Roll vs. Time. Roll Stability Step Test. UCK = 12 Knots. Rudder Ordered = 35^{o} 166
.2. Distrubance Moment vs. Time

119.1. Sternplane Angle vs. Time. Roll Stability Step Test. UCK = 12 Knots. Rudder Ordered = 35^{o} 167
.2. Disturbance Moment vs. Time

120.1. Sailplane Angle vs. Time. Roll Stability Step Test. UCK = 12 Knots. Rudder Ordered = 35^{o} 168
.2. Disturbance vs. Time

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Professor George J. Thaler for his encouragement and guidance during the preparation of this thesis.

I. INTRODUCTION

The importance of automatic control of pitch-depth and roll of a turning submarine has become more obvious with the improvements of high speed nuclear submarines. This study was aimed at smoothing the roll of a turning submarine in high speed, which is known as snap roll and causes the basic problem. Because of coupling between pitch and roll, before attempting to smooth the snap roll, controlling of pitch and depth in high speeds turns was also studied. In this study an automatic course controller was not considered.

The methods and techniques, which can be used to reduce and smooth the snap roll, can be categorized under two headings. The first concerns changes in the naval architectural characteristics of the designs, such as increasing GM (metacentric height) and reducing sail size. The second category involves those alternatives which make use of an automatic ship control system. Rudder sequencing and speed reduction fall under this classification. Reference 1 investigates the affect of increasing GM, reducing sail size and speed. In Reference 2, Stamps designed on automatic roll controller which makes use of rudder sequencing as a function of approach speed and instantaneous roll angles.

In recent studies, which were made by Naval Ship Research and Development Center (NSRDC), it was proposed to enhance the control of roll in high speed turns by using the Fairwater

planes differentially deflected so that they can be used to give a counter moment to reduce the roll. The investigation of the differentially deflected Fairwater planes effect was part of the project called "Improved Control For Advanced Submarines". The project was carried out under Program Element No. 62754N and Task Area 2F434001. The work unit number was 1-1563-001-74. In Reference 3, estimating the effectiveness of differentially deflected sailplanes was investigated as a part of project mentioned above. Reference 3 was the inspiration of this thesis and using differentially deflected sailplanes for direct control of roll was chosen as the design goal.

II. THE NATURE OF THE PROBLEM

Turning characteristics of a surfaced submarine, more or less, looks like those of a surface ship. But the situation in the submerged position shows big differences. These differences are the result of different naval architectural charactacteristics. Sail structure can be considered the main differences and the main source of roll problems. It is well known that when a surface ship goes into a turn, it experiences an initial inboard roll. After a very short transient it heels outboard. The reversing of the roll angle is primarily due to an asymmetric rudder. Since the submarine rudder is generally well submerged, the surfaced submarine has an outboard roll angle during both the initial and the steady state phase of a turn. For a typical submarine, at moderate speed this outboard roll angle is less than 10° and does not cause any big problem.

If a submerged submarine goes into a high speed turn, differences from the surfaced behavior are noticed and the problem becomes three-dimensionalized. In the very first phase of the turn, the ship has a small lateral velocity v and a small rotational velocity r. For a starboard turn, at some point along the centerline, X1, the lateral velocity due to r, rX1, equals the lateral velocity - v. (For symbols see Figure 1, 2, and Appendix A). The point, at which these two velocities are equal to each other, is called the instant center of turn. At some point, forward of the instant center, X_2, the lateral velocity, -v, gives a velocity component from

the starboard side. Along with the ahead velocity component of the ship, these velocities contribute an angle of attack from starboard. At this point, if the submarine has an appendage (sail), a lift force is produced on the sail directed to port. Depending on the sail configuration and the large moment arm of the sail. This force, directed to the port gives a small outboard (port) roll. In many submarines this outboard roll can not be felt.

In the steady state phase the angle of attack shifts to the other side (port) and results in an inboard roll. But contrary to the outboard roll this inboard roll is quite significant and at high speeds it can exceed 30° which is considered hazardous to both men and equipments. This inward roll is called the SNAP roll. In Figure 5, the roll characteristics of the ship to a constant 35° left rudder angle at 24 knots is shown. As can be seen, the initial outboard roll (in the simulation, outboard is the starboard side) is very small, less than 1°. But the snap roll reaches 37°.

Snap roll is not the only problem that can be faced when the submarine goes into a turn. Because of the appendage (which is mainly the sail), in the submerged position, submarines do not have very good hydrodynamics from this body structure. When the ship experiences a submerged turn the sail mainly destroys the waterflow around the hull. As a result a pressure difference is created between the upper portion of the hull and the bottom portion of the hull.

And a normal force results directed downward which bodily pushes the ship down. It is recalled that, in a turn, after the initial phase, the submarine has an inward roll with the deflected rudder. Rolling inward, causes this deflected rudder to act like a sternplane which gives the submarine a down pitch movement. All of these effects come together and cause the ship to rise or dive depending on the peculiarity of its design. As it is stated in Reference 4, "The exact mechanism of this is not well understood". In Figures 3, 4, and 6, the depth, pitch, and rudder response of the ship, to a 35° left rudder angle at 24 knots is shown. It is interesting to indicate here that after a long transient period, the submarine starts to rise with the bow down eventhough it dives initially. It should be remembered that in this simulation of the model, no control surface (stern and fairwater plane) was used. The changes of these characteristics will be seen after the depth-pitch and roll controller is designed.

The complexity of controlling the turning submarine mainly comes from the coupling between the roll and pitch. Since roll and pitch are coupled, to be able to control the roll, which is our primary concern, pitch control to some extent must be accomplished. In the following sections a pitch and depth controller is designed by using only the sternplanes because of the goal of using the fairwater plane as a main part of the direct roll controller.

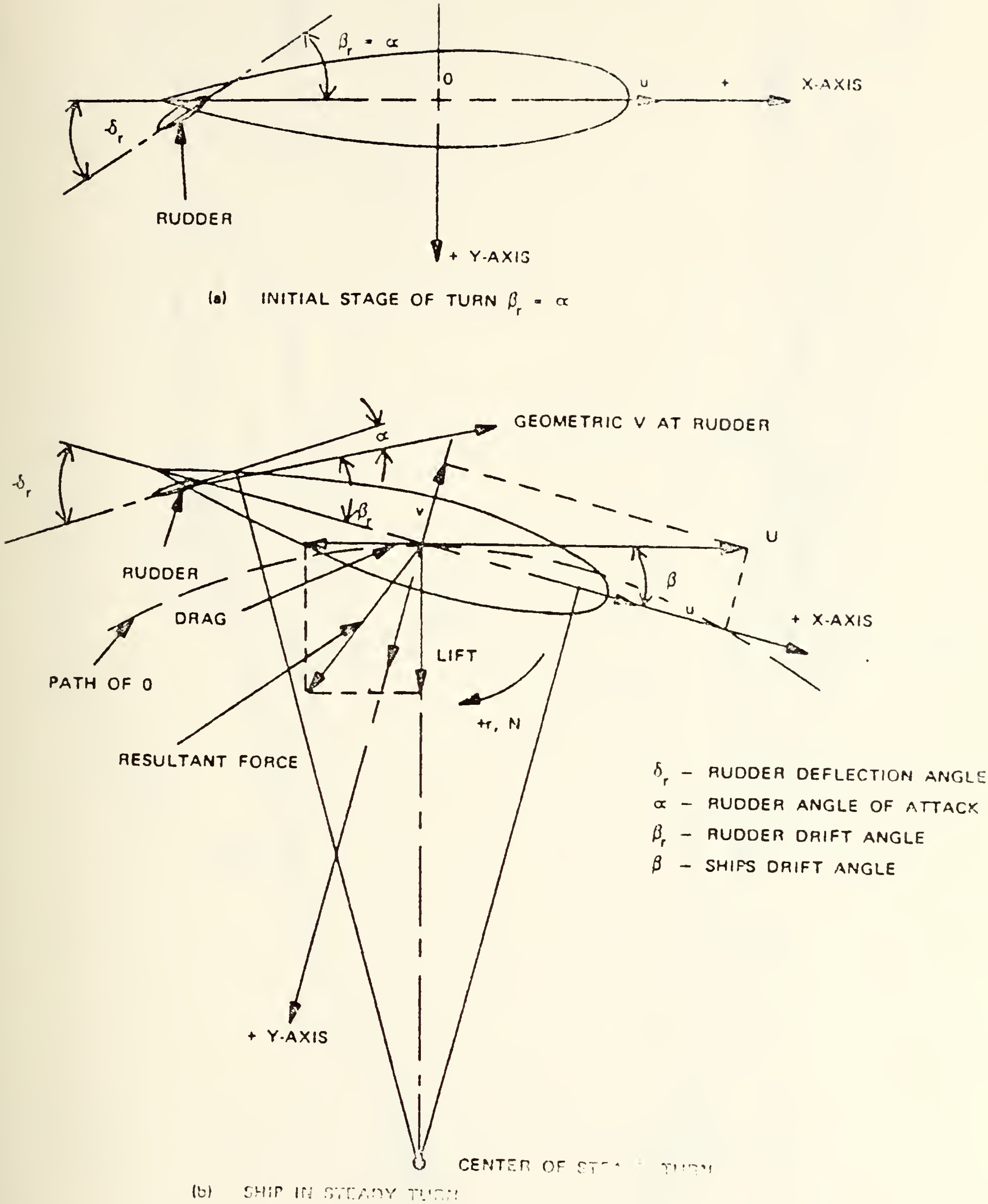


Figure 1. Hydrodynamic Forces In A Turn.
(After Reference 4)

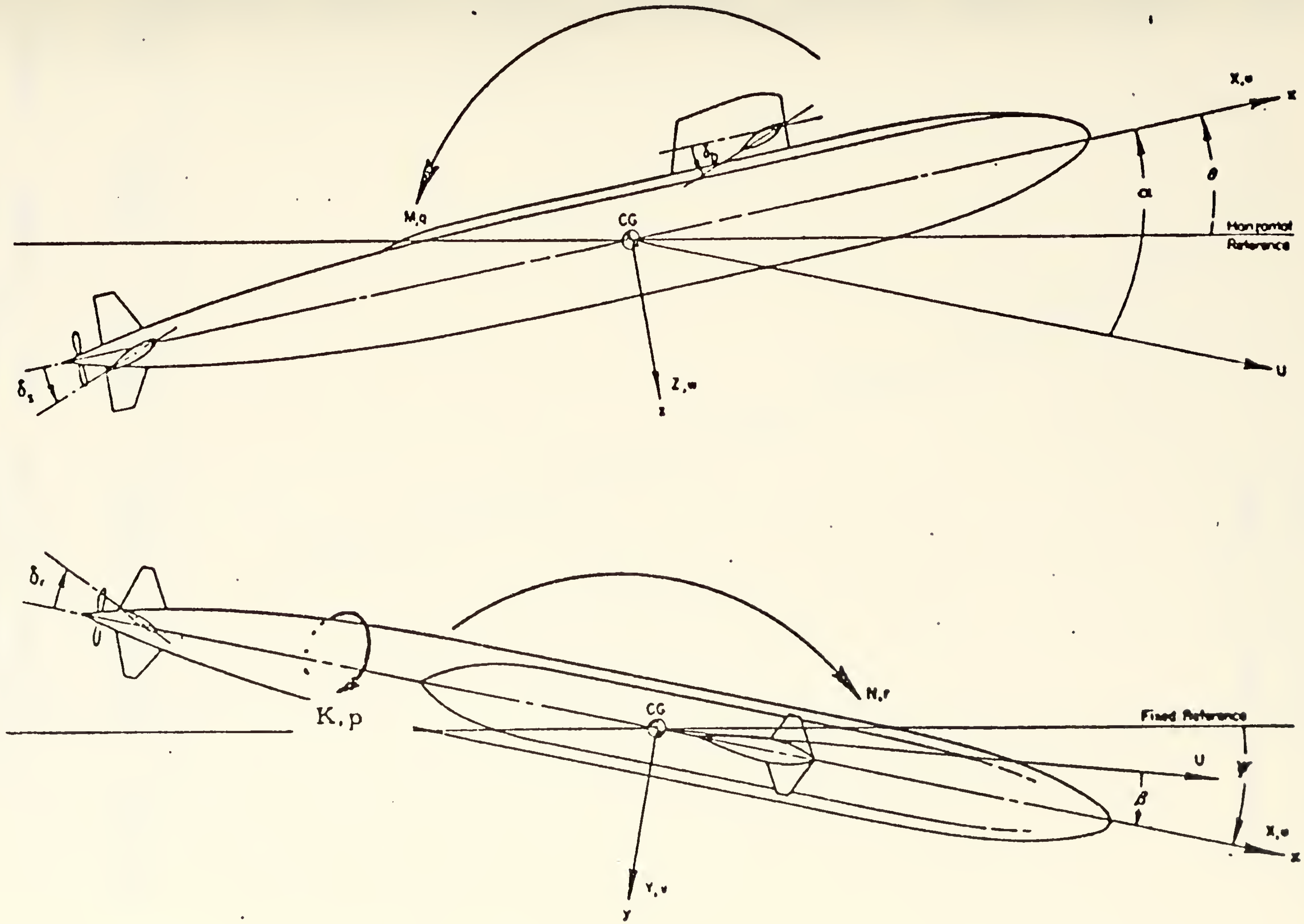


Figure 2. Submarine Axes
(After Reference 5)

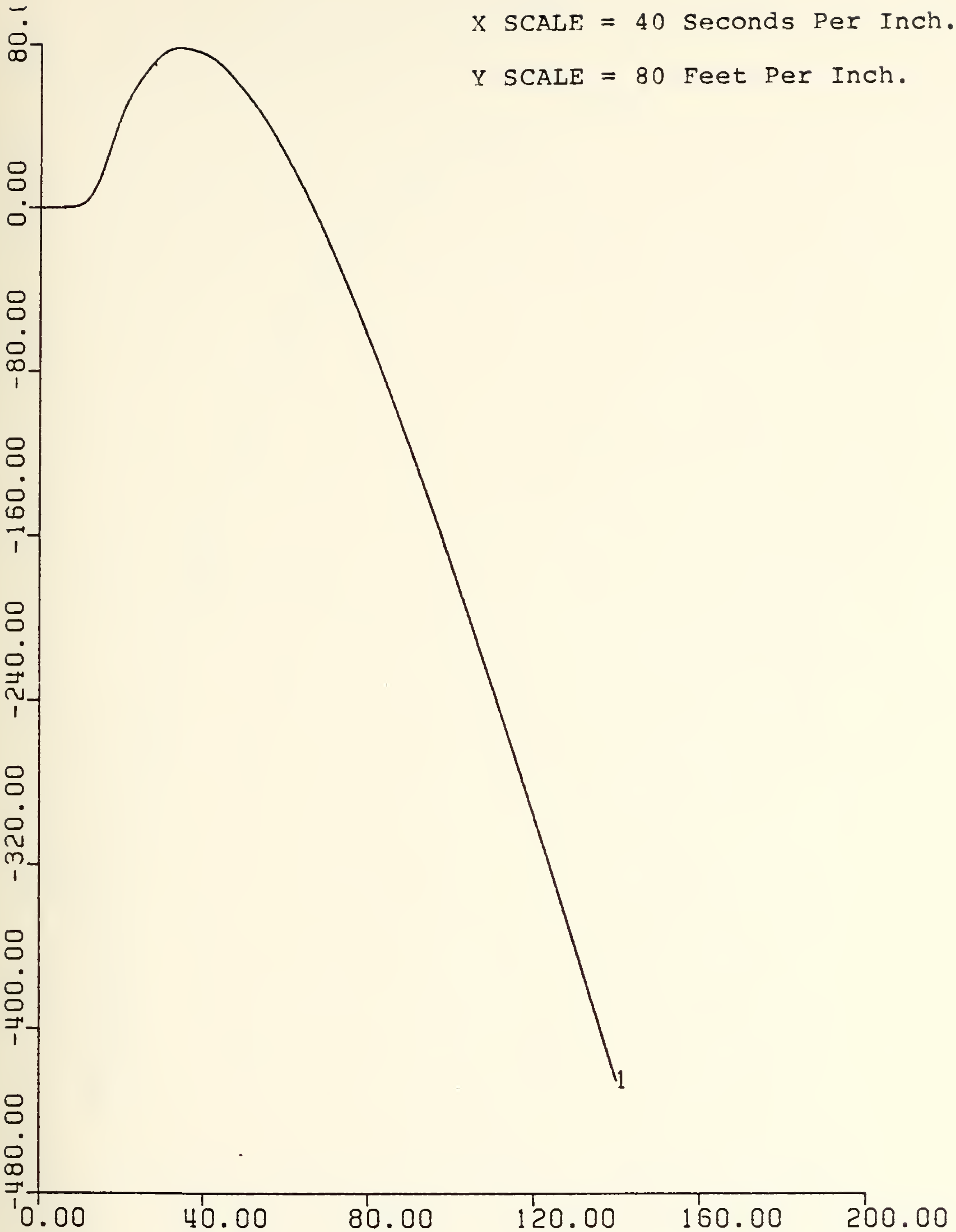


Figure 3. Depth vs. Time. With No Controller
UCK = 24 Knots. Rudder Ordered = 35°.

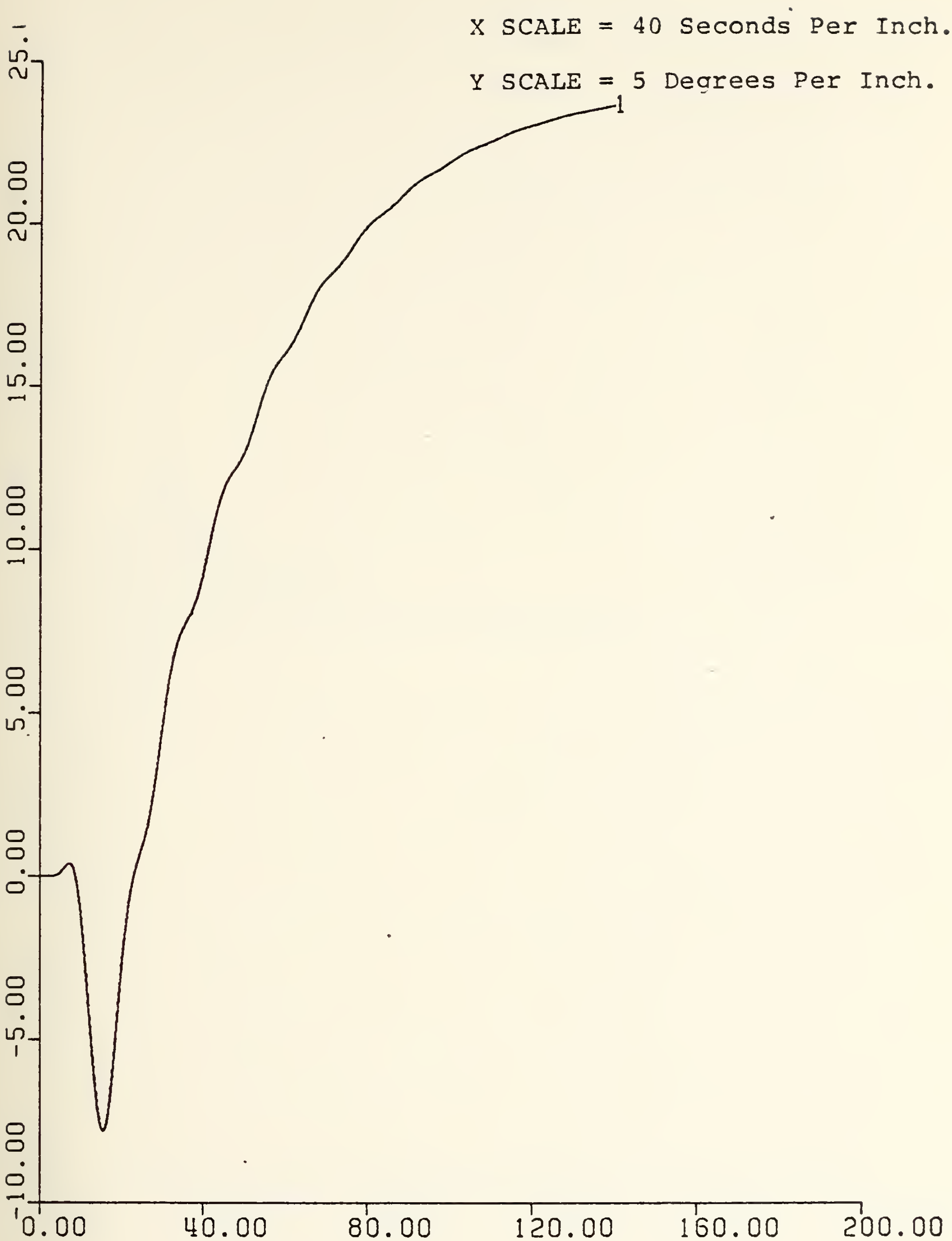


Figure 4. Pitch vs. Time. With No Controller.
UCK = 24 Knots. Rudder Ordered = 35°.

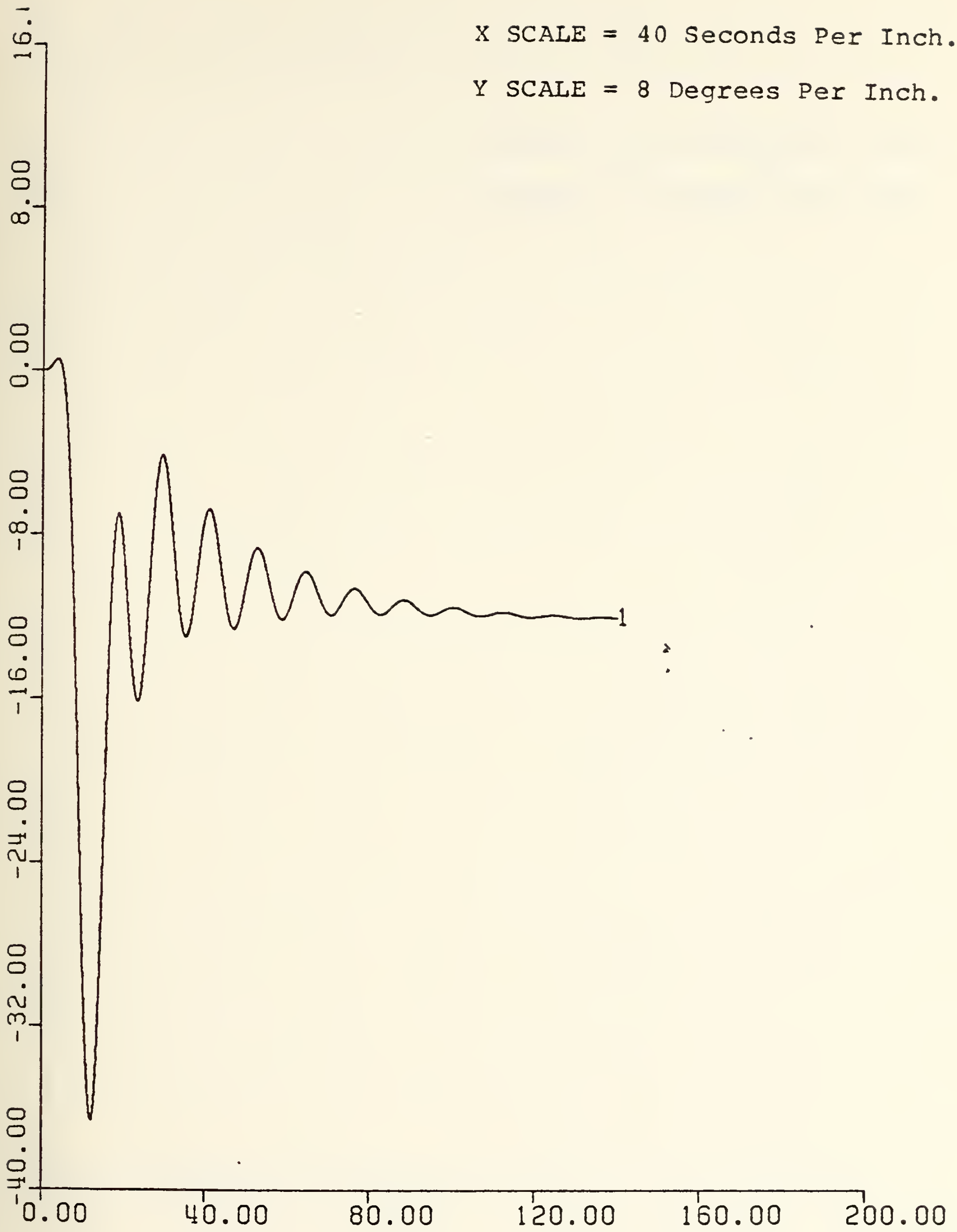


Figure 5. Roll vs. Time. With No Controller. UCK = 24 Knots. Rudder Ordered = 35°.

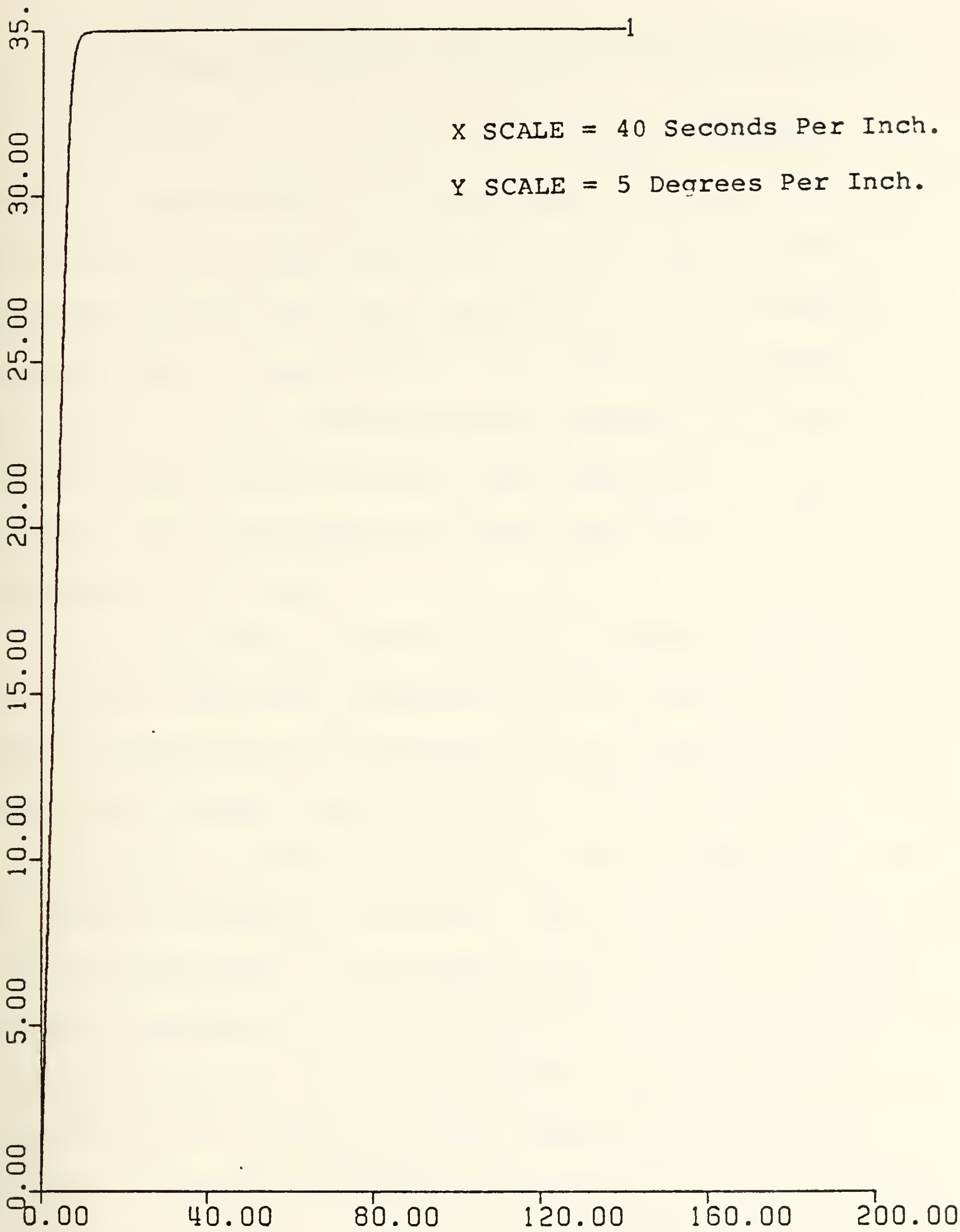


Figure 6. Rudder Response vs. Time. With No Controller. UCK = 24 Knots. Rudder Ordered = 35°.

III. DIGITAL COMPUTER SIMULATION OF SUBMARINE MOTION

The mathematical model of the totally submerged submarine is represented by the equations of motion which consist of six equations such that each of them represent the force and moment equations on and around the three rectangular coordinate axes. These equations were derived by NSRDC in Reference 5 and for convenience was repeated in Appendix A. In this thesis, derivation of these equations was not our concern. More pronounced knowledge about that can be found in References 4, 5, and 6.

The equations of motion, which represent the motion of the totally submerged submarine, in six degree of freedom, consist of Hydrodynamic coefficient, in undimensionalized form except the m (mass) and I_x, I_y, I_z (three moments of inertia). In Reference 7, Drurey translated these six equations into the DSL (digital simulator language) form and originated the computer program which is the mathematical model of the ship. For the necessity of using the hydrodymanic coefficients in undimensionalized form, the equations containing I_x, I_y, I_z, both sides are divided by l^5 and these three moments of inertia were used in undimensionalized form. For the same reason the equations containing m were divided by l^3.

Since the trim control of the ship was not considered in this study the ship was assumed in the trimmed condition.

For trimming the ship the hydrodynamic coefficient Z_* and M_* were set to zero. These two hydrodynamic coefficients represent the force and moment acting on the ship when the control surfaces are at zero deflection.

Since all of the simulations of this study were done in a turn, an accurate simulation must include the rudder actuator dynamics such that any phase lag could not produce any unstability. Actuator dynamics used in this thesis was the same as used in Reference 3 with the rudder deflection angle 5^{o}/sec., so that at the end of the study it could give acceptable comparison level between the two designs. A block diagram of the rudder actuator is shown in Figure 7.

Since our prime concern is to control the roll as well as the depth and the pitch when the submarine is in a turn, a series of tests were run at different speeds to validate the models originated in Reference 7 by Drurey. The model was highly satisfactory as shown in Figures 8 through 25. These figures record responses in depth, pitch, roll, yaw, speed changes, and rudder angle at 18, 12, and 6 knots. In this test, turn was commanded 10 seconds after the simulation started, to validate the initial condition response of the model. Since the submarine was trimmed by eliminating Z_* and M_*, it is seen that until the turn was commanded all responses are zero. Simulation at 24 knots was already shown in Figures 3 through 6.

It was observed that, at 6 knots the ship continues diving unlike the simulation of 12, 18, and 24 knots. The

reason for this was that at low speed enough pressure difference to cause the ship to rise slowly could not be created.

After the validation of the model it was decided to proceed with the designing of the controllers. In the following sections first, the depth and pitch controller design was studied. An optimal control scheme such as in Reference 7 was used. The sternplanes was the control surface of the controller, and the fairwater plane was saved for use in the roll controller.

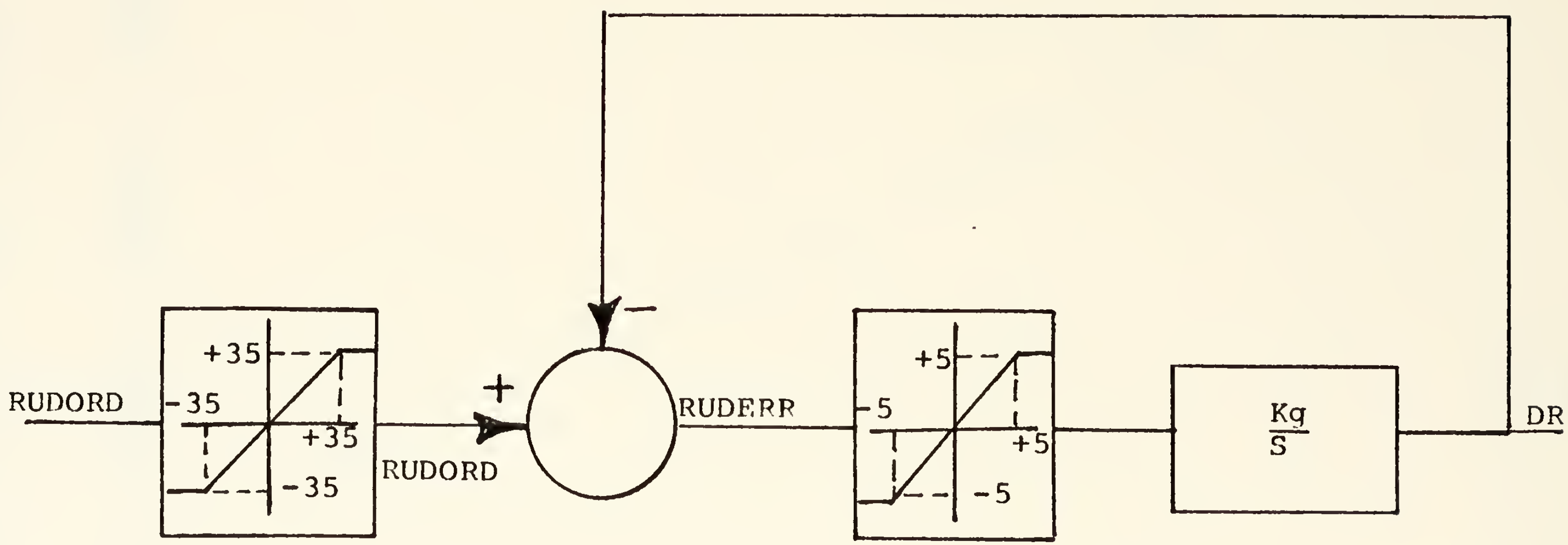


Figure 7. Rudder Actuator Model. (After Reference 2)

Figure 8. Depth vs. Time. With No Controller.
UCK = 18 Knots. Rudder Ordered = 35°.

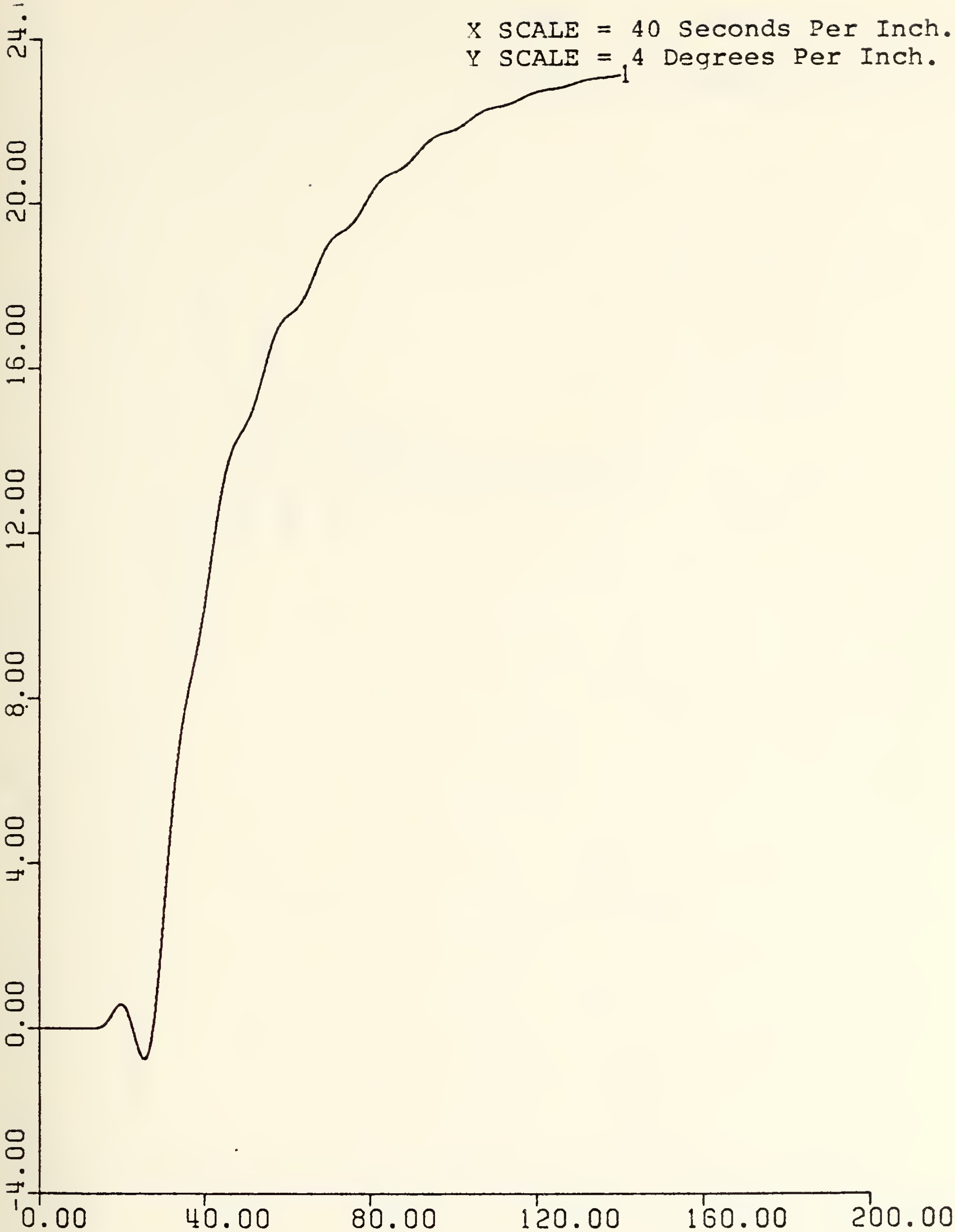


Figure 9. Pitch vs. Time. With No Controller.
UCK = 18 Knots. Rudder Ordered = 35°.

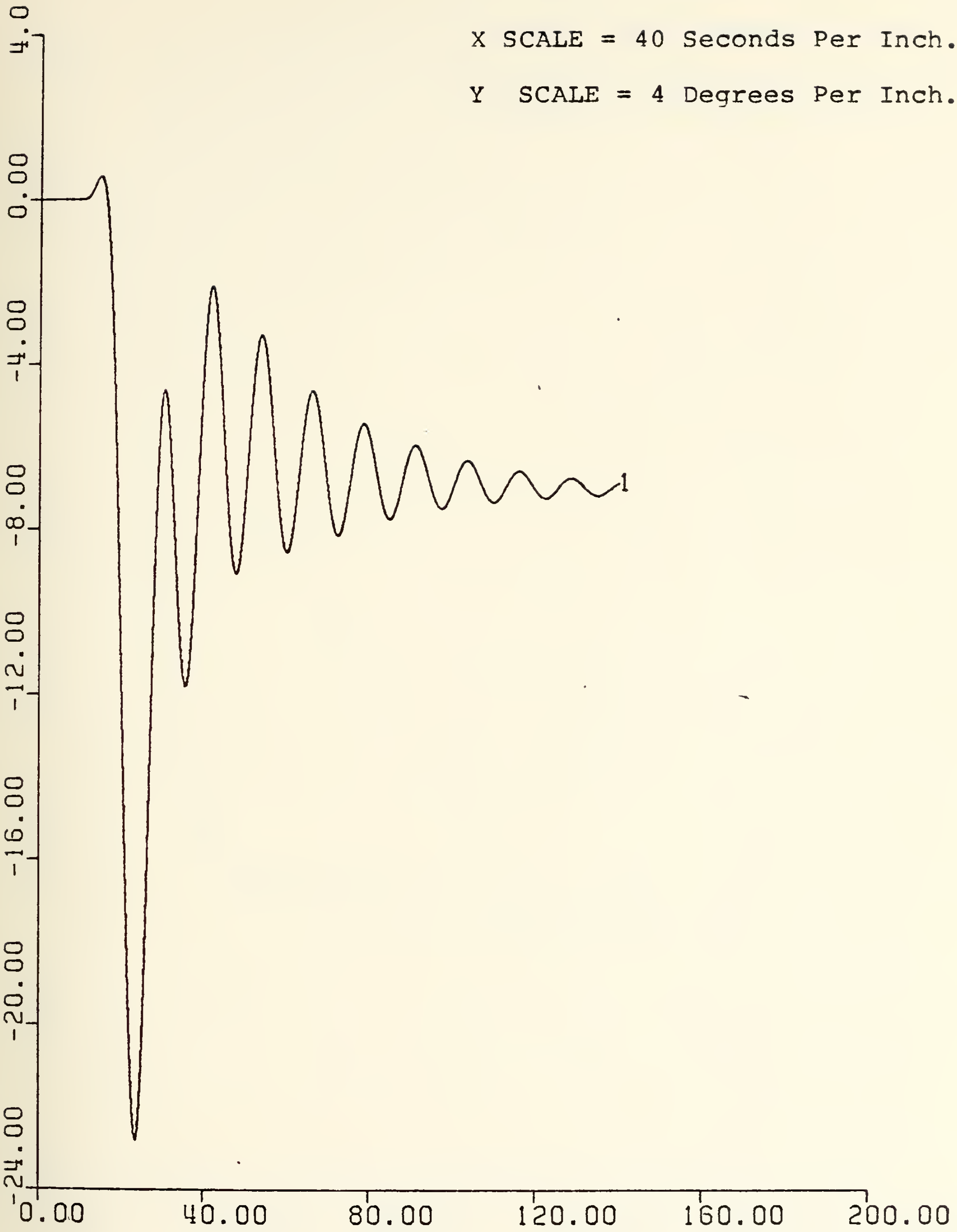


Figure 10. Roll vs. Time. With No Controller.
UCK = 18 Knots. Rudder Ordered = 35°.

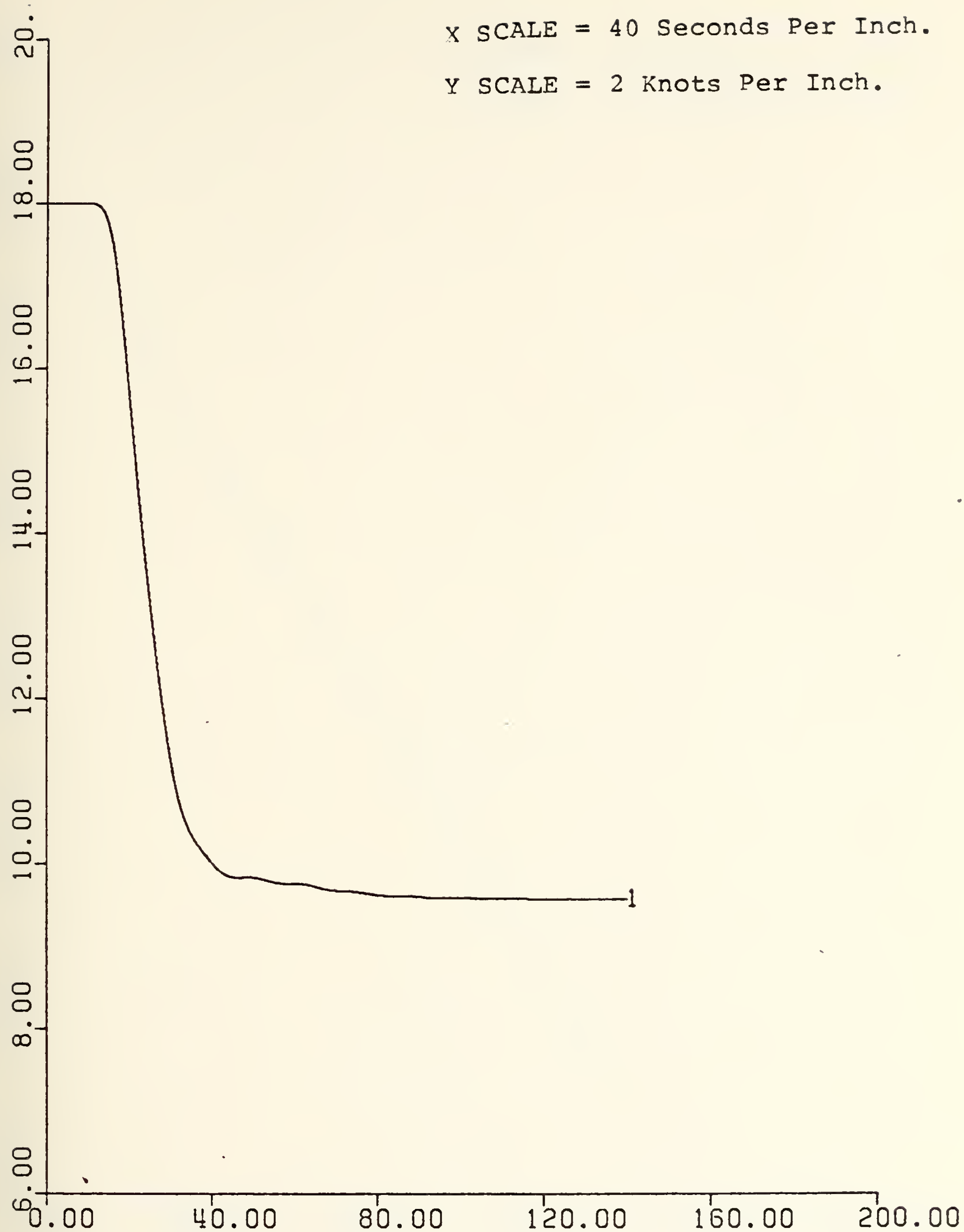


Figure 11. Speed Change vs. Time. With No Controller. UCK = 18 Knots. Rudder Ordered = 35°.

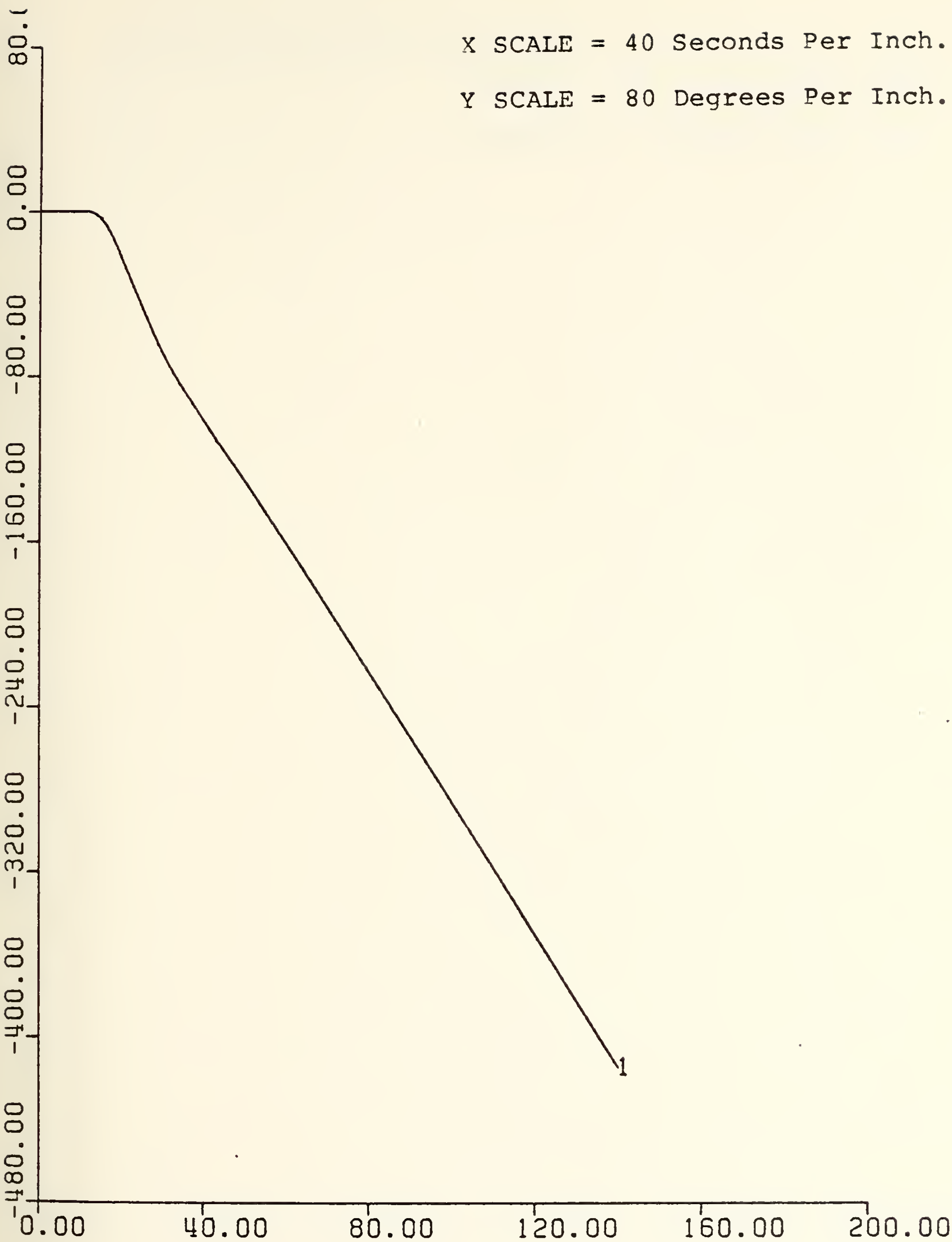


Figure 12. Yaw vs. Time. With No Controller.
UCK = 18 Knots. Rudder Ordered = 35°.

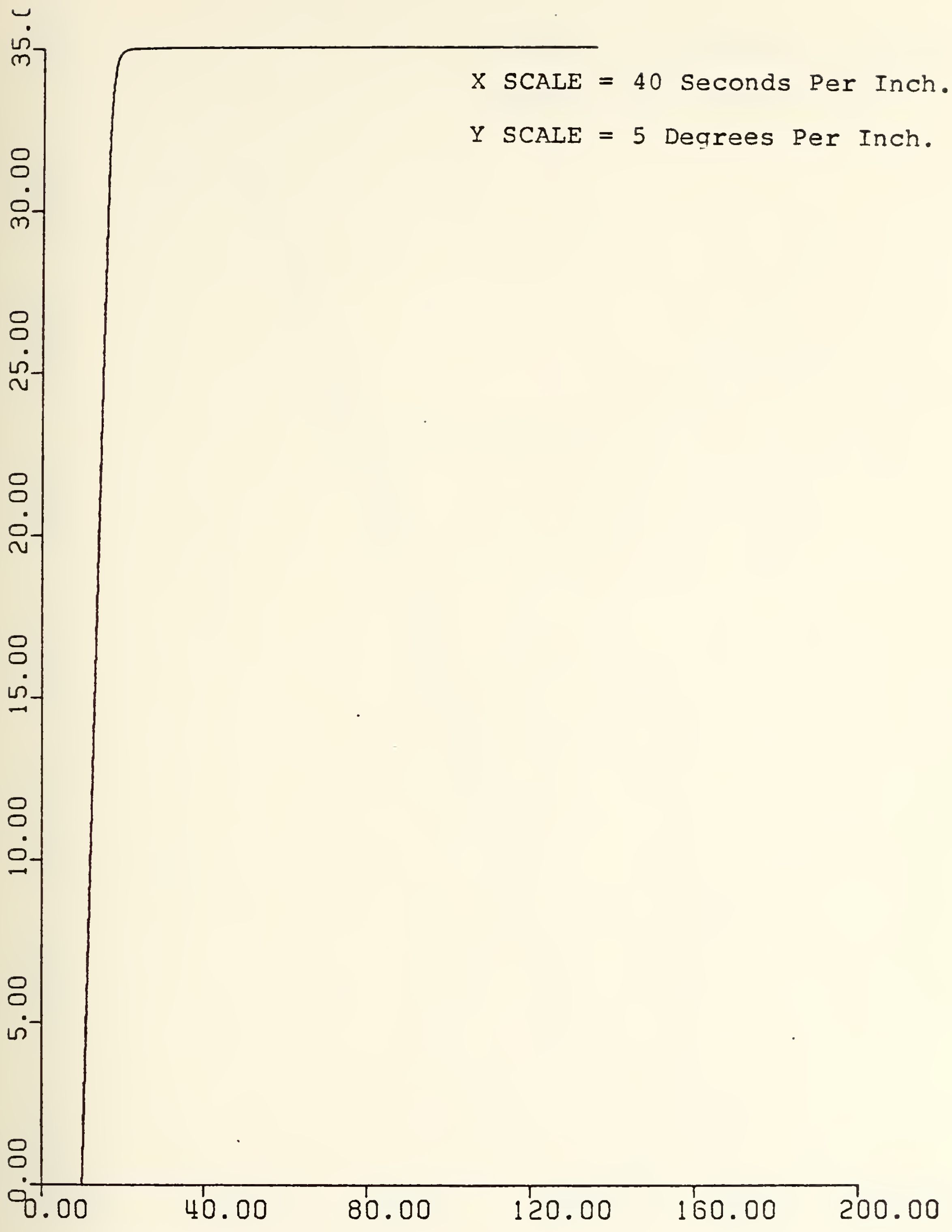


Figure 13. Rudder Response vs. Time.
UCK = 18 Knots. Rudder Ordered = 35°.

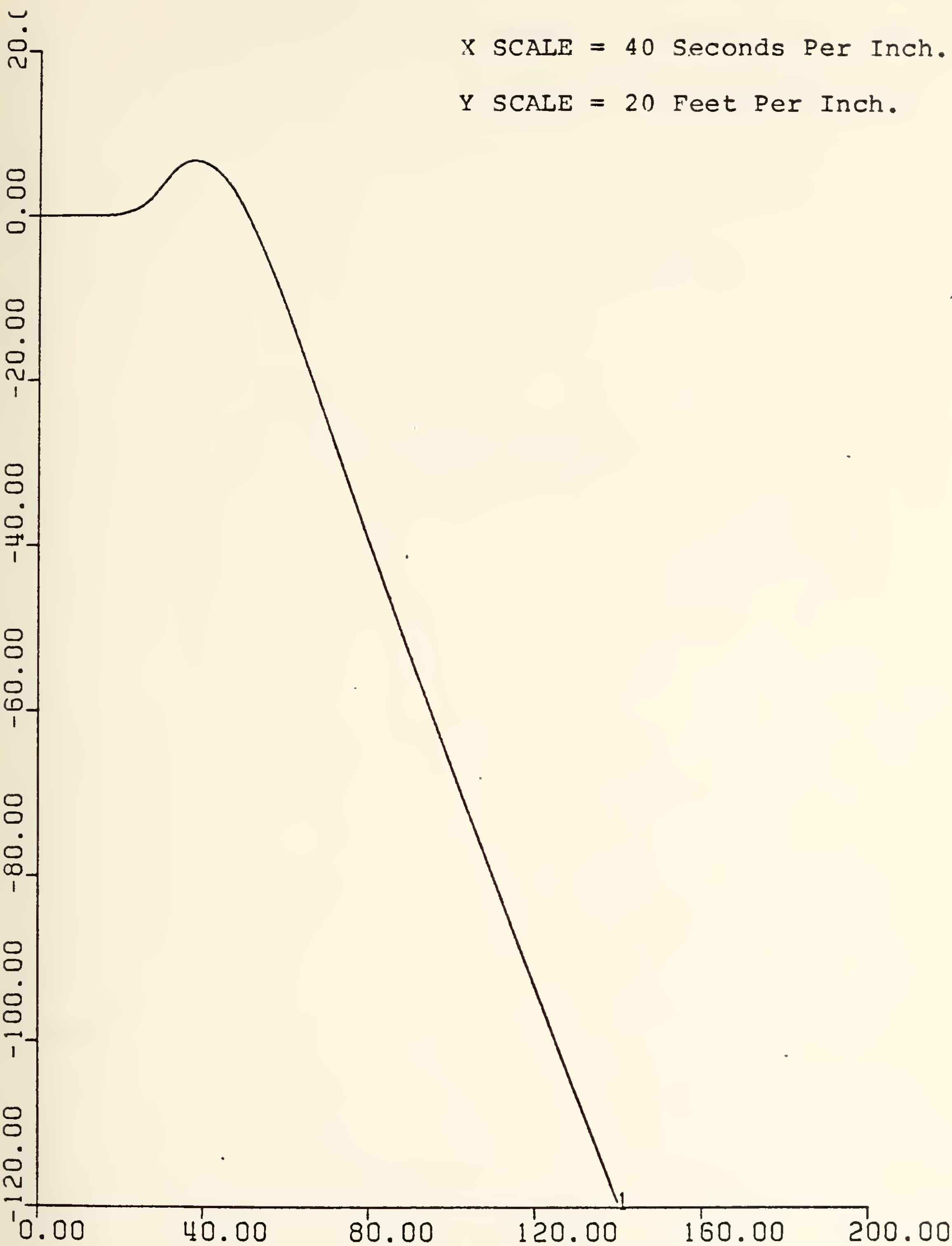


Figure 14. Depth vs. Time. With No Controller.
UCK = 12 Knots. Rudder Ordered = 35°.

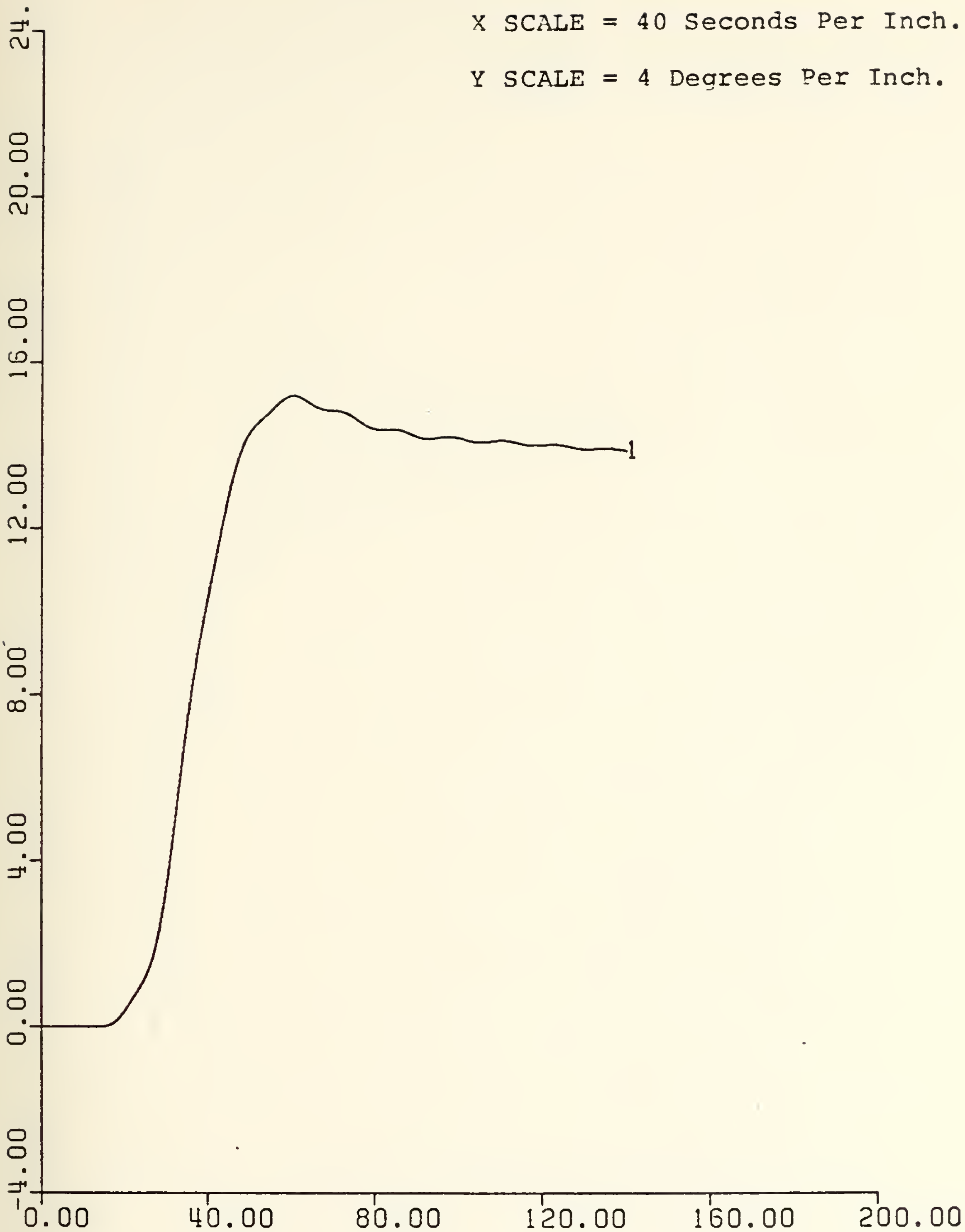


Figure 15. Pitch vs. Time. With No Controller.
UCK = 12 Knots. Rudder Ordered = 35°.

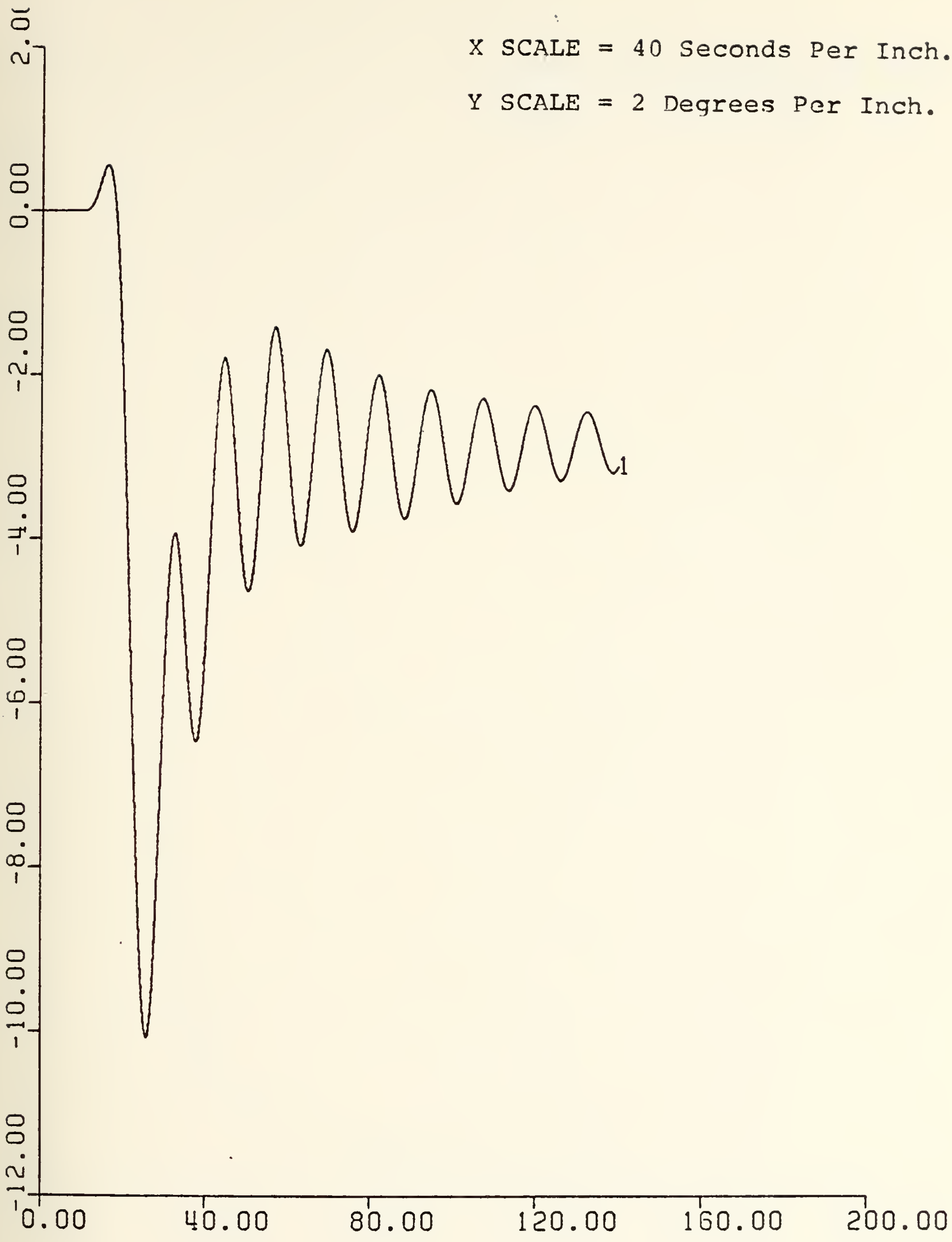


Figure 16. Roll vs. Time. With No Controller. UCK = 12 Knots. Rudder Ordered = 35°.

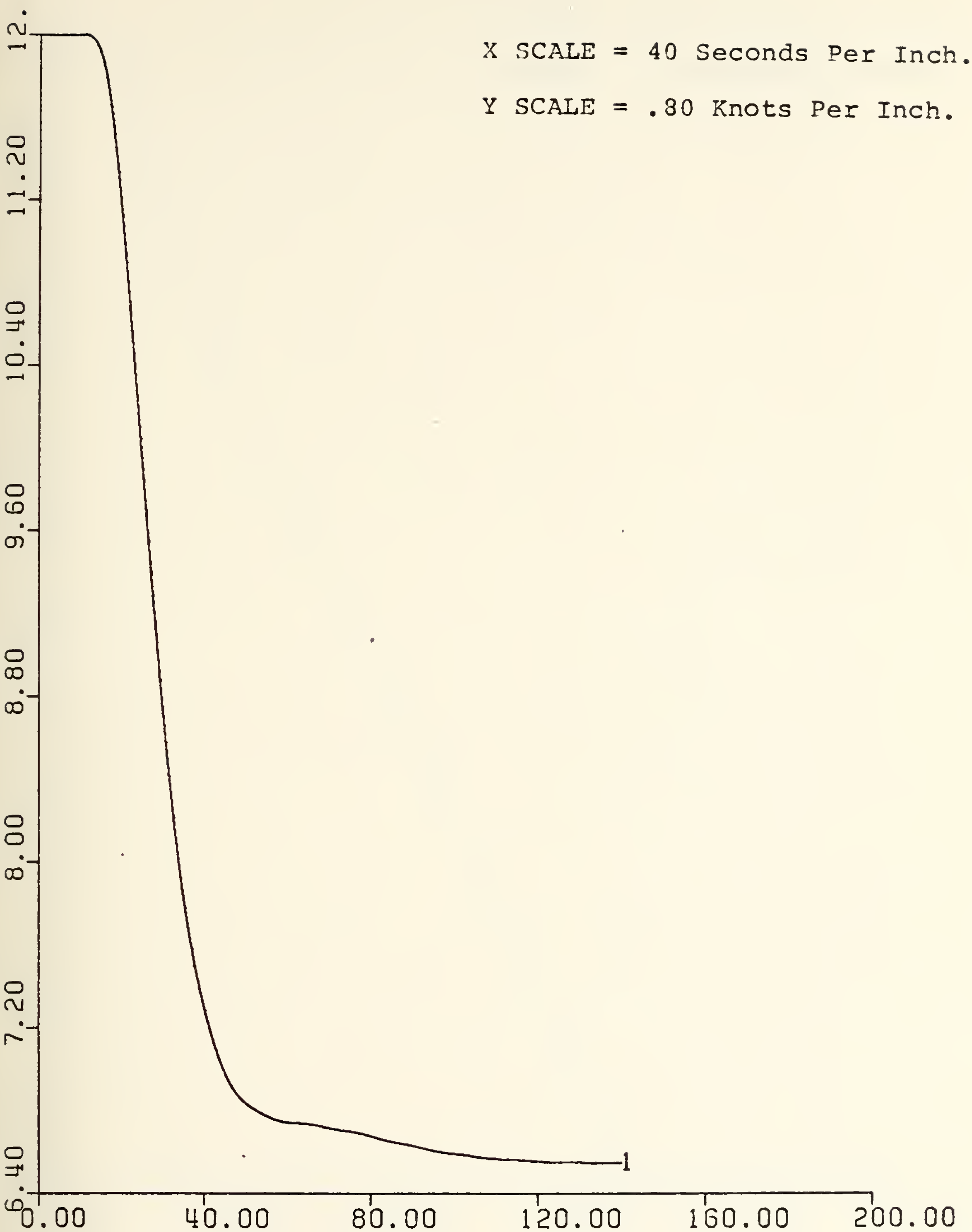


Figure 17. Speed Change vs. Time. With No Controller. UCK = 12 Knots. Rudder Ordered = 35°.

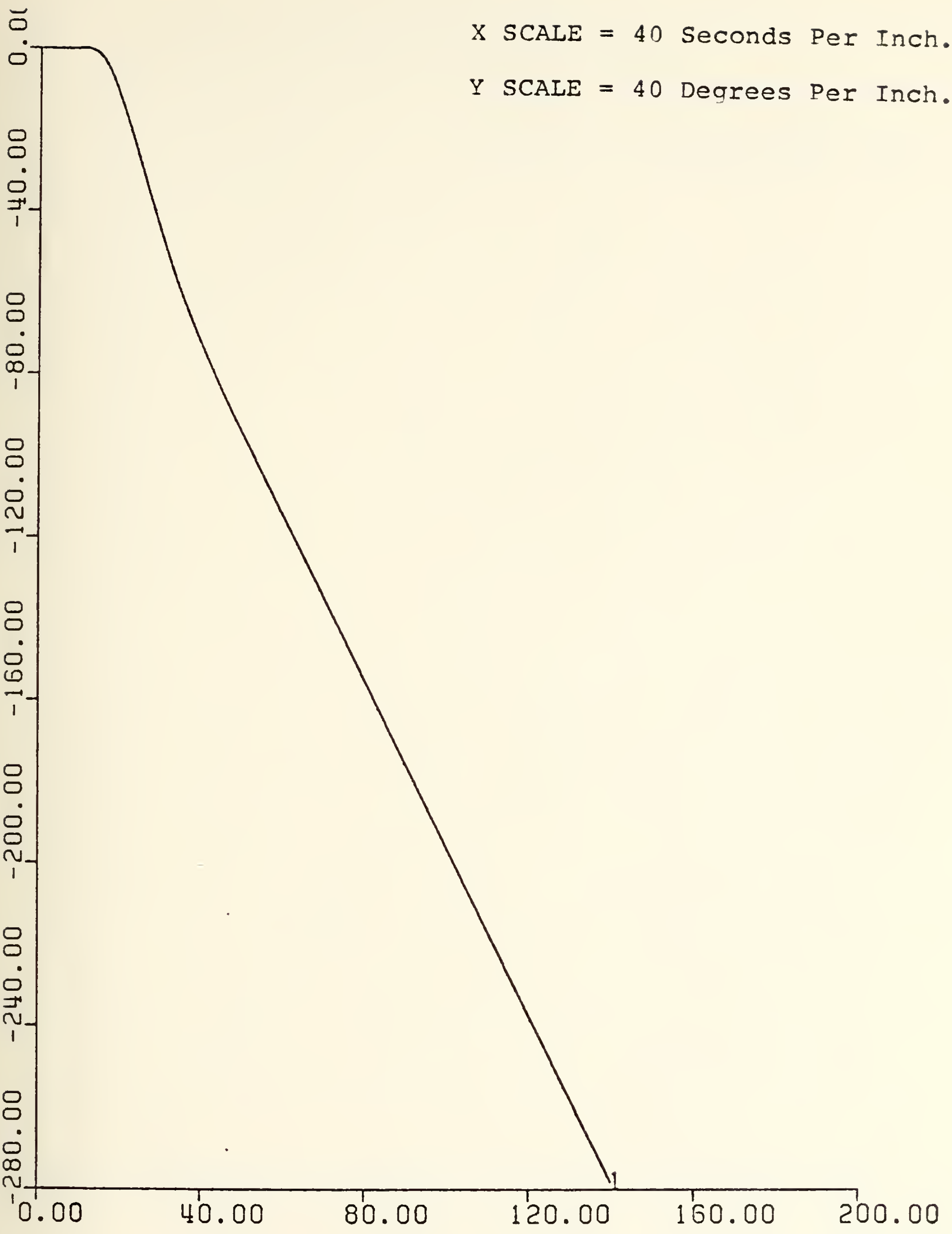


Figure 18. Yaw vs. Time. With No Controller.
UCK = 12 Knots. Rudder Ordered = 35°.

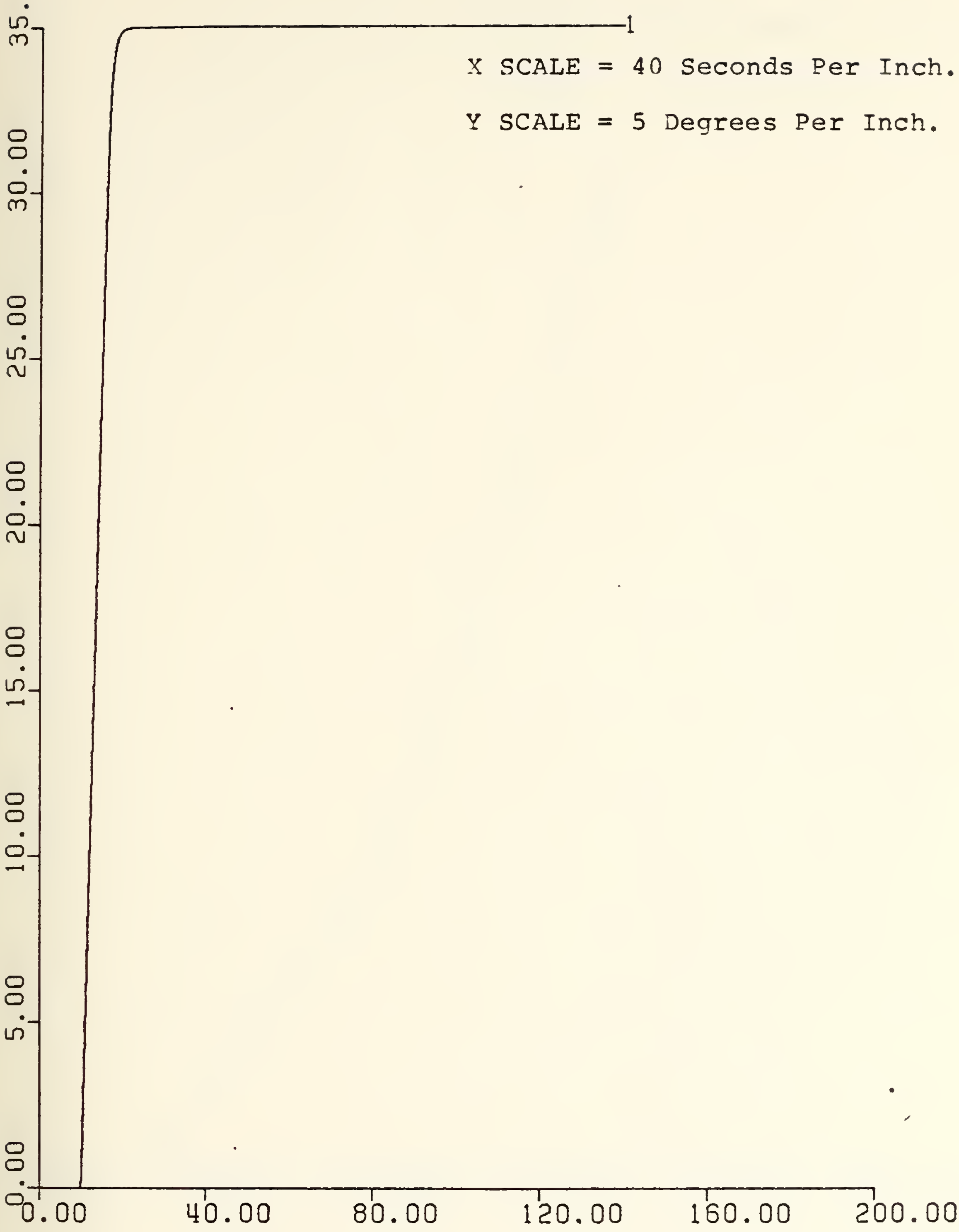


Figure 19. Rudder Response vs. Time. With No Controller. UCK = 12 Knots. Rudder Ordered = 35°.

Figure 20. Depth vs. Time. With No Controller.
UCK = 6 Knots. Rudder Ordered = 35°.

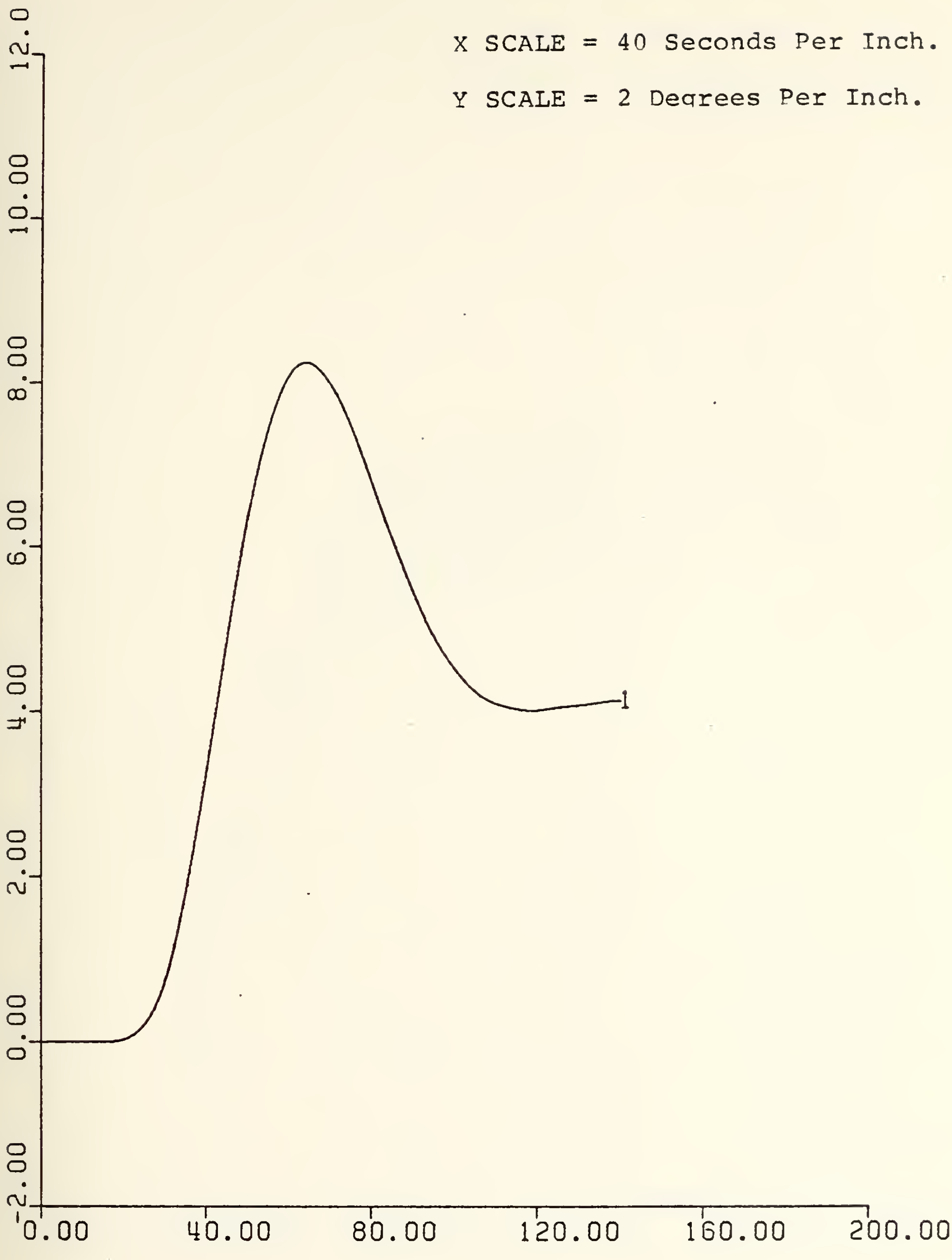


Figure 21. Pitch vs. Time. With No Controller.
UCK = 6 Knots. Rudder Ordered = 35°.

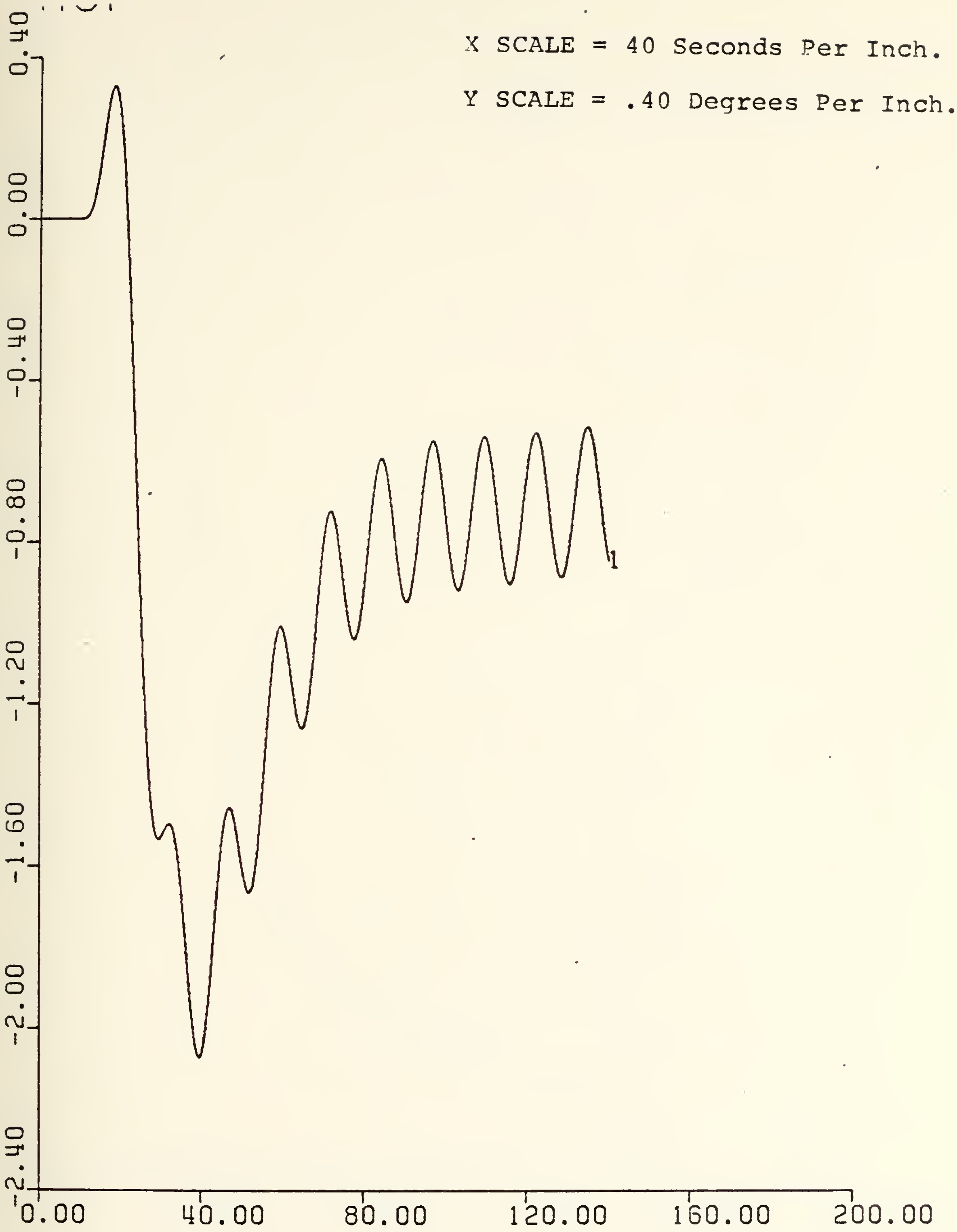


Figure 22. Roll vs. Time. With No Controller.
UCK = 6 Knots. Rudder Ordered = 35°.

Figure 23. Speed Change vs. Time. With No Controller. UCK = 6 Knots. Rudder Ordered = 35°.

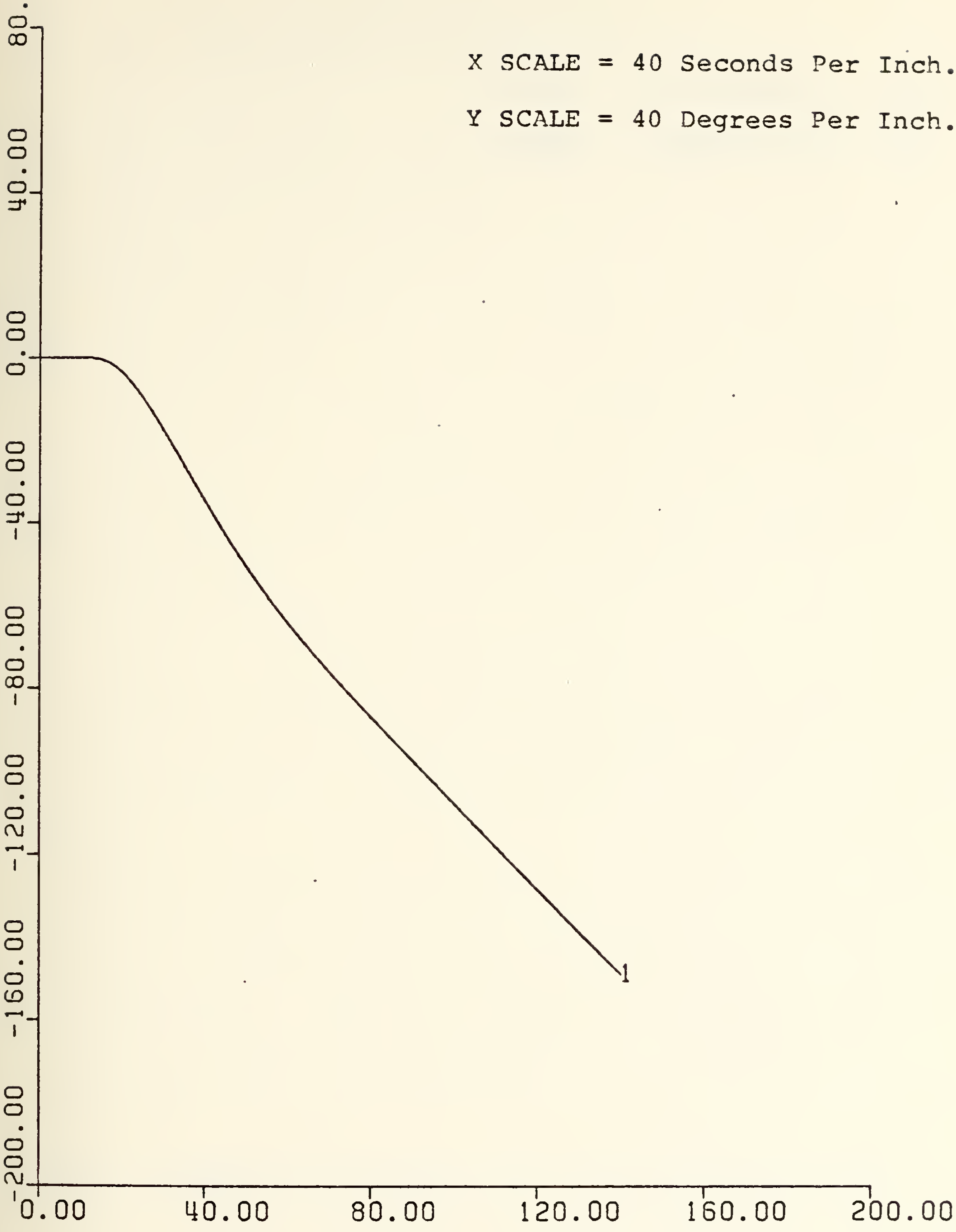


Figure 24. Yaw vs. Time. With No Controller.
UCK = 6 Knots. Rudder Ordered = 35°.

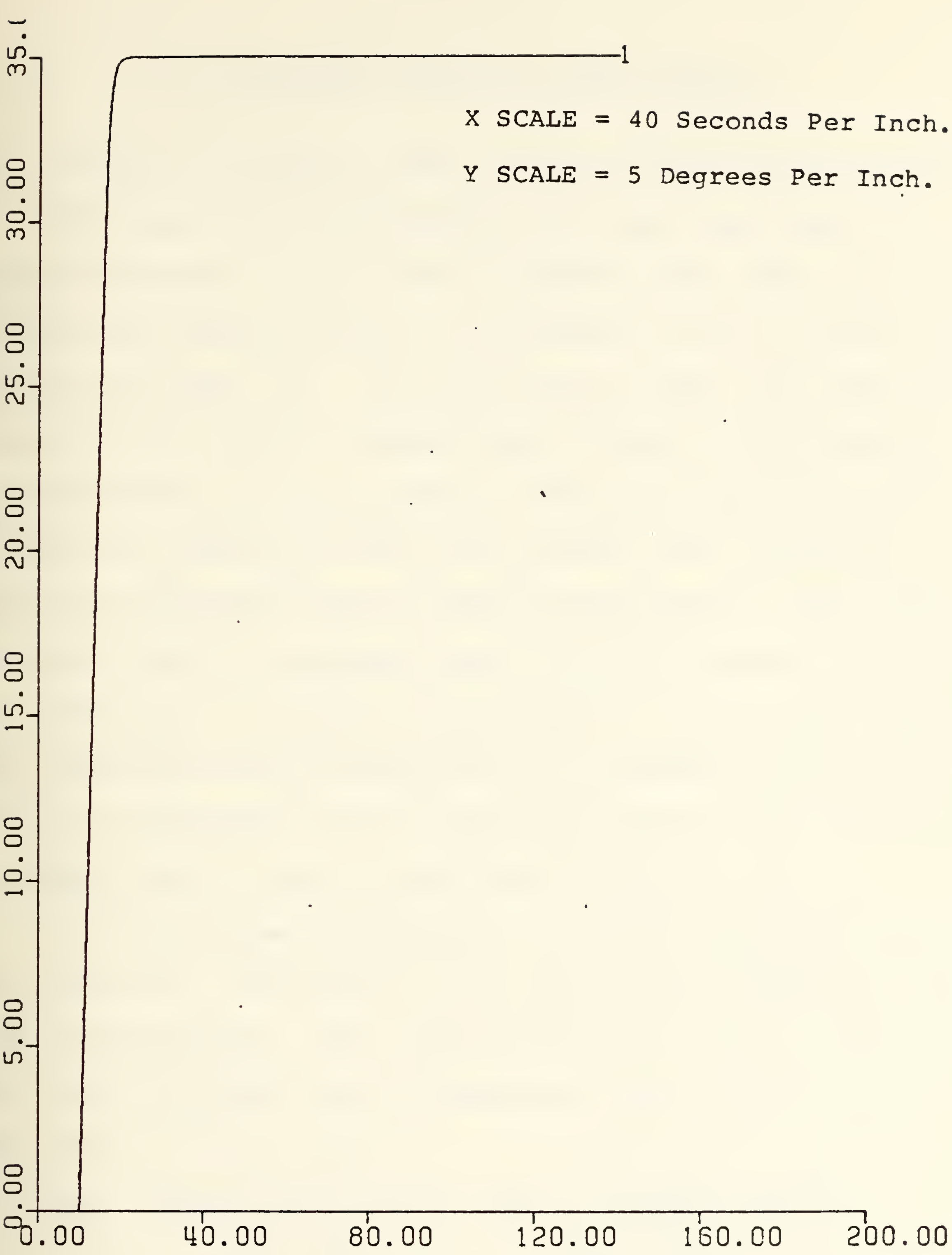


Figure 25. Rudder Response vs. Time. With No Controller. UCK = 6 Knots. Rudder Ordered = 35°.

IV. AUTOMATIC DEPTH AND PITCH CONTROL

A. OPTIMAL SOLUTION TO THE LINEARIZED SUBMARINE EQUATIONS

The necessity of controlling the depth and pitch of a turning submarine, as was stated before, stems from the coupling between the states such that any changes of one of them directly affects the other one. For this reason, depth and pitch control to some extent must be accomplished so that it can provide a good stage for the roll control. There are many ways of controlling the depth and pitch which depend upon the way of using stern and fairwater control surfaces combination. The scheme that was used in this thesis was an optimal control way which was originated by Drureys in Reference 7. To preclude unnecessary repetition, only guidelines of the method and the differences of this study are to be discussed here. More pronounced knowledge can be found at Reference 7 and 8.

It can be seen in Appendix A that the equations of motion are nonlinear. To be able to use this set of equations, they must be linearized. This linearization was done in Reference 7, and with one control input (sternplane) they can be written in the form of:

$$\begin{bmatrix} m-Z\dot{w} & -l\cdot Z\dot{q} \\ -m\dot{w}/_l & I_y-M\dot{q} \end{bmatrix} \begin{bmatrix} \dot{W} \\ \dot{Q} \end{bmatrix} = \begin{bmatrix} u\cdot Zw/_l & UZq \\ U.Mw/_{l2} & U.M\dot{q}/_l \end{bmatrix} \begin{bmatrix} W \\ Q \end{bmatrix} + \begin{bmatrix} U^2\ Zds/_l \\ U^2 Mds/_{l2} \end{bmatrix} DS$$

If they are put in state variable form

$$\begin{bmatrix} \dot{W} \\ \dot{Q} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{21} \\ A_{12} & A_{22} \end{bmatrix} \begin{bmatrix} W \\ Q \end{bmatrix} + \begin{bmatrix} B_{11} \\ B_{12} \end{bmatrix} DS$$

Where

$$\text{Determ} = \left[(I_y - M\dot{q})(m - Z\dot{w}) - M\dot{w}Z\dot{q}\right]$$

$$A_{11} = \left[(I_y - M\dot{q})Zw + Z\dot{q}Mw\right] u/l \cdot \text{Determ}$$

$$A_{12} = \left[M\dot{w}Zw + (m - Z\dot{w})Mw\right] u/l^2 \cdot \text{Determ}$$

$$A21 = \left[(I_y - M\dot{q})Zq + Z\dot{q}Mq\right] u/ \text{Determ}$$

$$A22 = \left[M\dot{w}Zq + (m - Z\dot{w})Mq\right] u/l \cdot \text{Determ}$$

$$B11 = \left[(I_y - M\dot{q})Zds + Z\dot{q}Mds\right] u^2/l \cdot \text{Determ}$$

$$B12 = \left[M\dot{w}Zds + (m - Z\dot{w})Mds\right] u^2/l^2 \cdot \text{Determ}.$$

The problem was thought as a linear regulator problem. The general scheme of linear regulator problem is shown in Figure 26.

The cost function is

$$J = \frac{1}{2} \int_{t_o}^{t_f} \left[E^T Q E + U^T R U\right] dt$$

$E = X - r$ and r is the reference vector which is

$$r = \begin{bmatrix} \text{ordered depth} \\ \text{ordered pitch} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

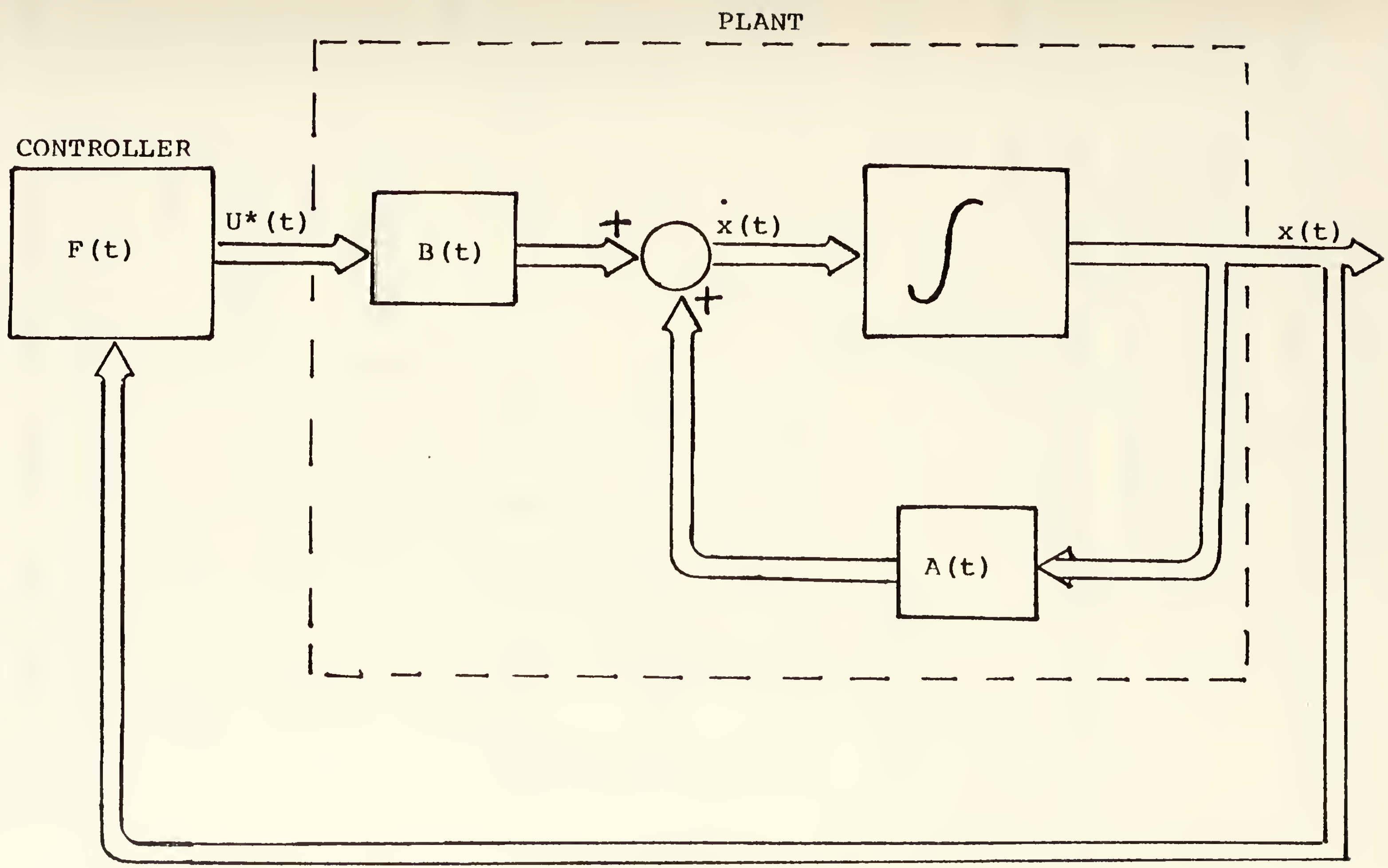


Figure 26. Plant And Optimal Feedback Controller For Linear Regulator Problem.

As a result

$$E = X \text{ can be written.}$$

Following the Reference 7 and 8

$$\dot{K} = -KA+KBR^{-1}B^{T}K-Q-A^{T}K \text{ and}$$

$$U = -R^{-1}B^{T}KE \text{ can be written.}$$

If the linear equations are augmented and put in the state equation form with the definition

$$E = X = \begin{bmatrix} W \\ Q \end{bmatrix} \qquad \text{and } U = Ds$$

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & -u & 0 \\ 0 & A_{11} & 0 & A_{21} \\ 0 & 0 & 0 & 1 \\ 0 & A_{12} & 0 & A_{22} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} + \begin{bmatrix} 0 \\ B_{11} \\ 0 \\ B_{12} \end{bmatrix} Ds$$

Where

$$\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} = \begin{bmatrix} \text{Depth Rate} \\ \text{Depth} \\ \text{Pitch Rate} \\ \text{Pitch} \end{bmatrix}$$

In this study, in order to make the depth rate a state variable the following transformation was used

Depth rate $= w-u\cdot\theta$ where w represent the component of u in the z direction, θ represents the pitch angle. In

Reference 7 this transformation was originally

Depth Rate = w and the differences between these two transformations showed itself in the calculation of K values which is discussed in the following pages.

Referring to the cost function

$$Q = \begin{bmatrix} E & 0 & 0 & 0 \\ 0 & A & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & B \end{bmatrix} \qquad R = C$$

and

$$K = \begin{bmatrix} K_{11} & K_{21} & K_{31} & K_{41} \\ K_{12} & K_{22} & K_{32} & K_{42} \\ K_{13} & K_{23} & K_{33} & K_{43} \\ K_{14} & K_{24} & K_{34} & K_{44} \end{bmatrix}$$

The selection of the weighting factors was a trial and error process. The series of weighting factors depending upon the relative severity of the influence of the states to each other was tested and as a result

E = Depth Error Weighting = 10

D = Pitch Error Weighting = 8000

C = Control Input Weighting = 100

A = B = 0 was chosen.

After solution of $n(n+1)/_2$ differential equations, K values associated with the feedback gain was found. It is observed that steadstate values of K are constant which is a

convenient condition for optimality. Results of this solution are shown in Figures 27 through 36. For comparison the original A matrix of Reference 7 with the transformation Depth rate = w was also used to calculate K values. One of the results is shown in Figure 37. It is observed that it could not reach steady state value in the reasonable time period.

After K values associated with the feedback gains were found, necessary gains were found via the optimal low.

$$u = -\frac{1}{R} B^T K E$$

The result was

$$u = DSAD = -0.31623*Z0ER-1.792*Z0DOT + 36.069*PERR = 102.63*P1DOT.$$

All of the feedback gains were found at 15 knots speed. It is obvious that these gains associated with the hydrodynamic coefficient used are function of the speed. To make the gains compatible with the speed range of the ship, they must be scaled with the function of the speed. In Reference 2, the controller gains adjustment as a function of the speed was discussed deeply and found that gains associated with the depth rate and pitch role error channel was inversely proportional to the instantaneous speed as gains associated with the depth and pitch error channel remains same. After the justification of these results

$$DSAD = -0.31623*Z0ER-1.792*(15)/_{UK} *Z0DOT + 36.069*PERR + 102.63*(15)/_{UK} *P1DOT$$

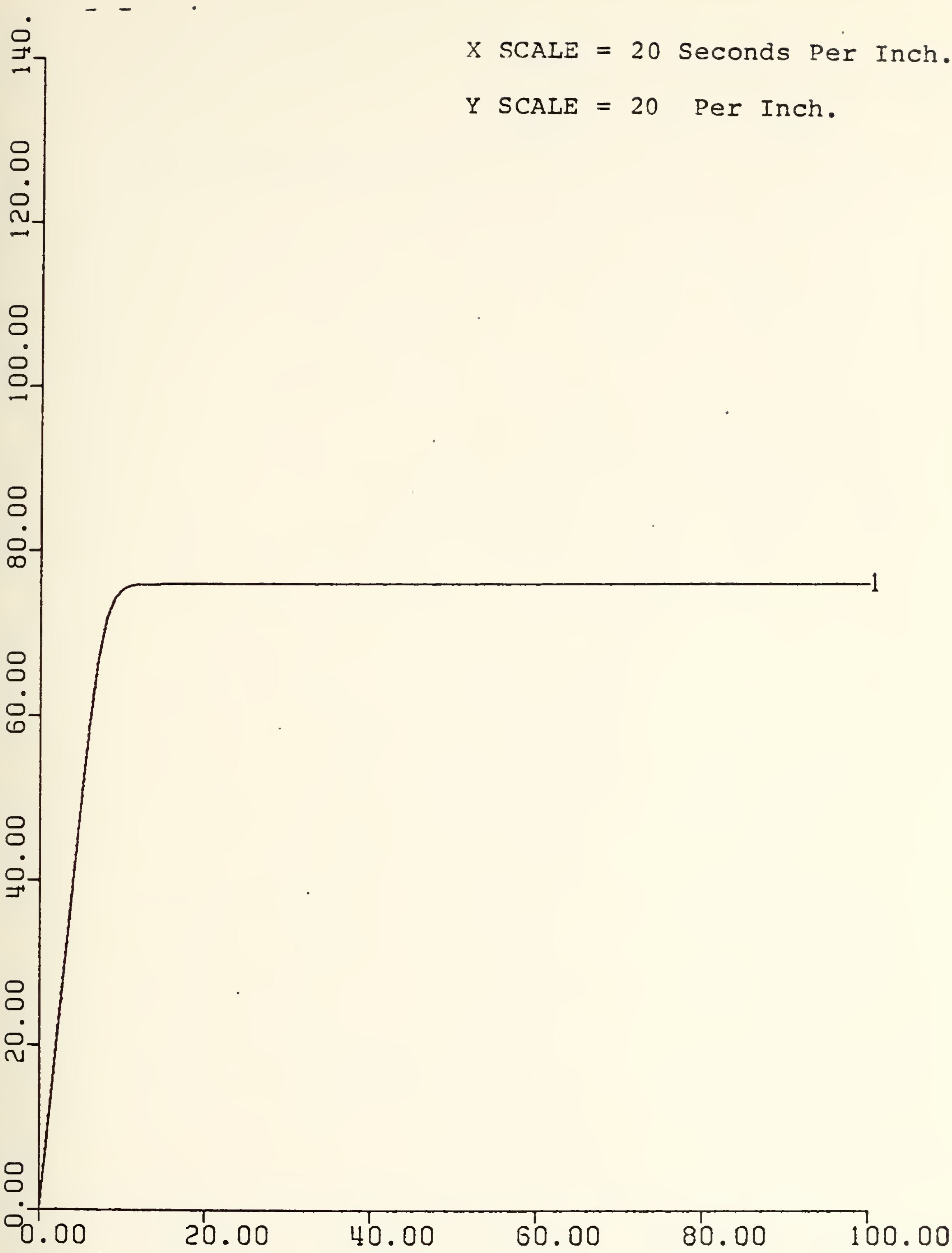


Figure 27. K11 vs. Time. UCK = 15 Knots.
D = 8000, A = 0, E = 10, B = 0, C = 100.

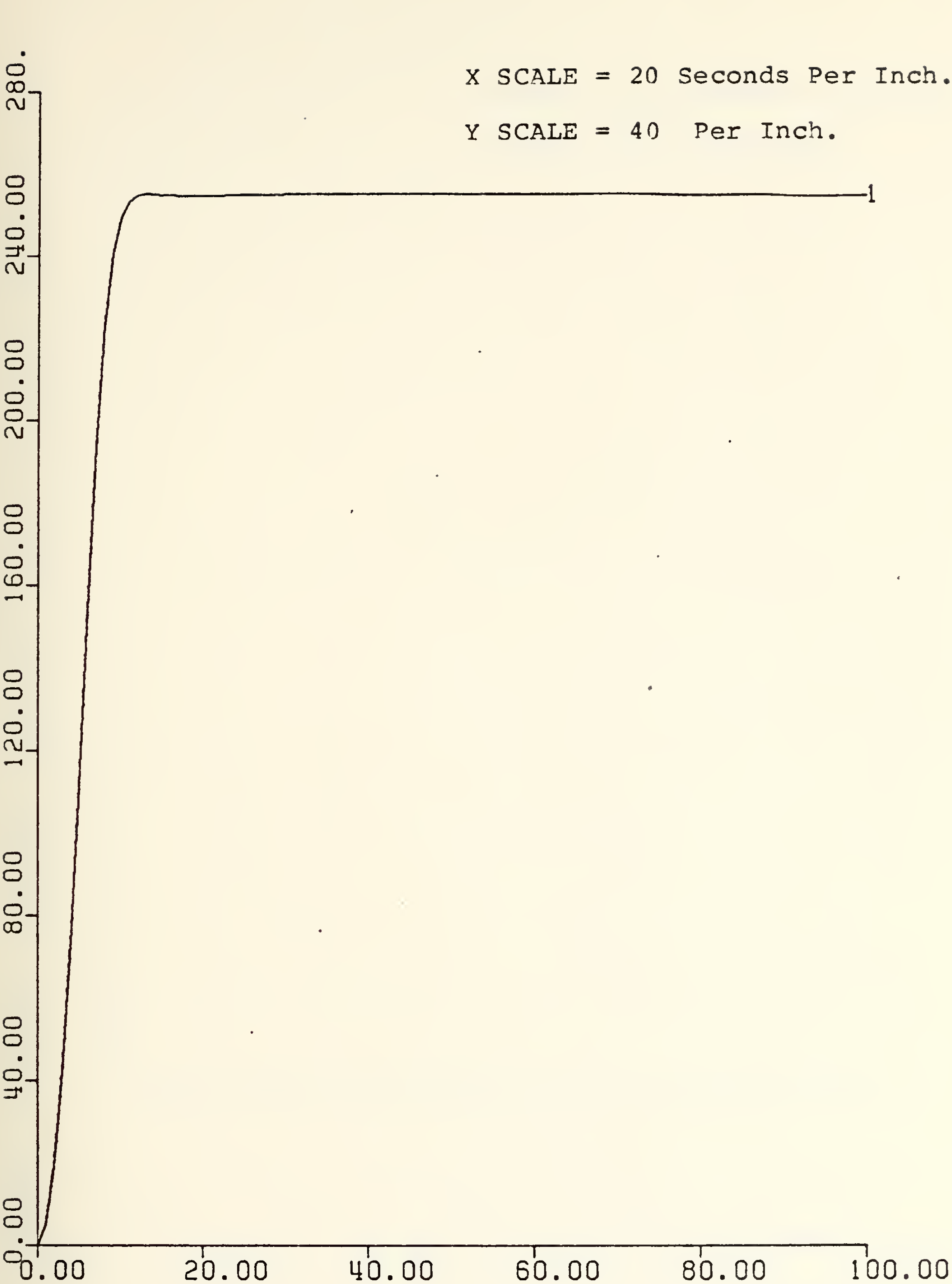


Figure 28. K12 vs. Time. UCK = 15 Knots.

D = 8000, A = 0, E = 10, B = 0, C = 100.

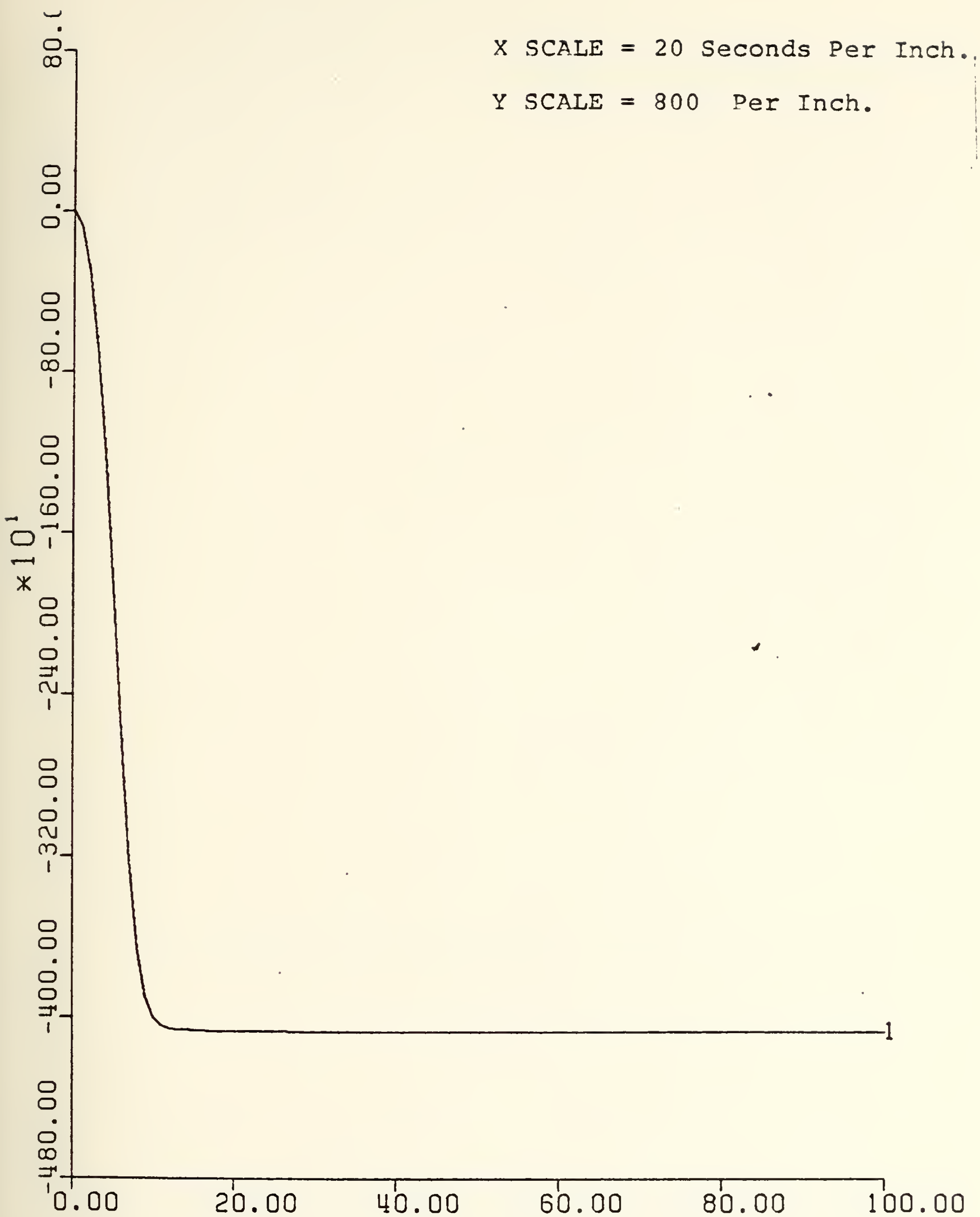


Figure 29. K13 vs. Time. UCK = 15 Knots.
D = 8000, A = 0, E = 10, B = 0, C = 100.

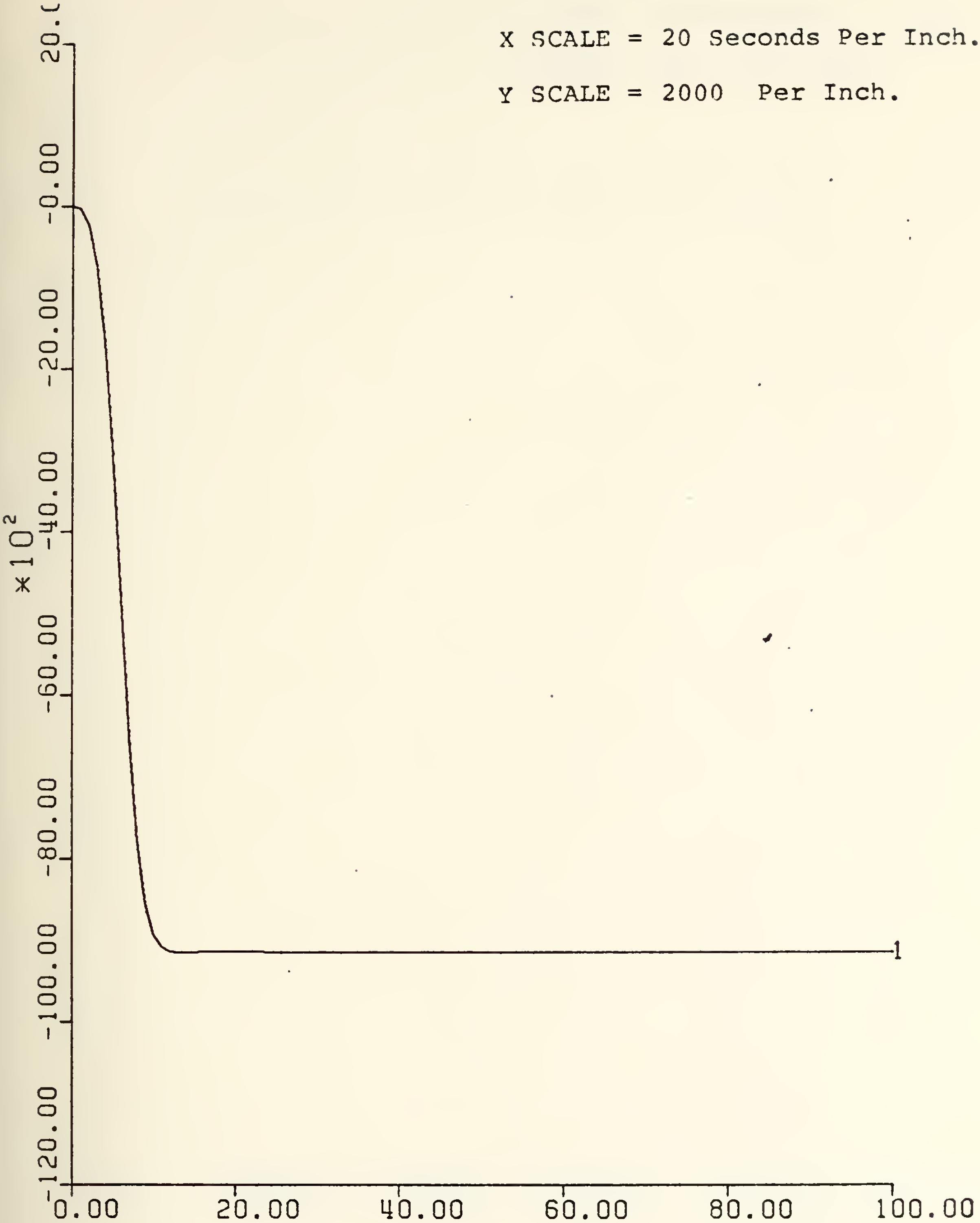


Figure 30. K14 vs. Time. UCK = 15 Knots.
D = 8000, A = 0, E = 10, B = 0, C = 100.

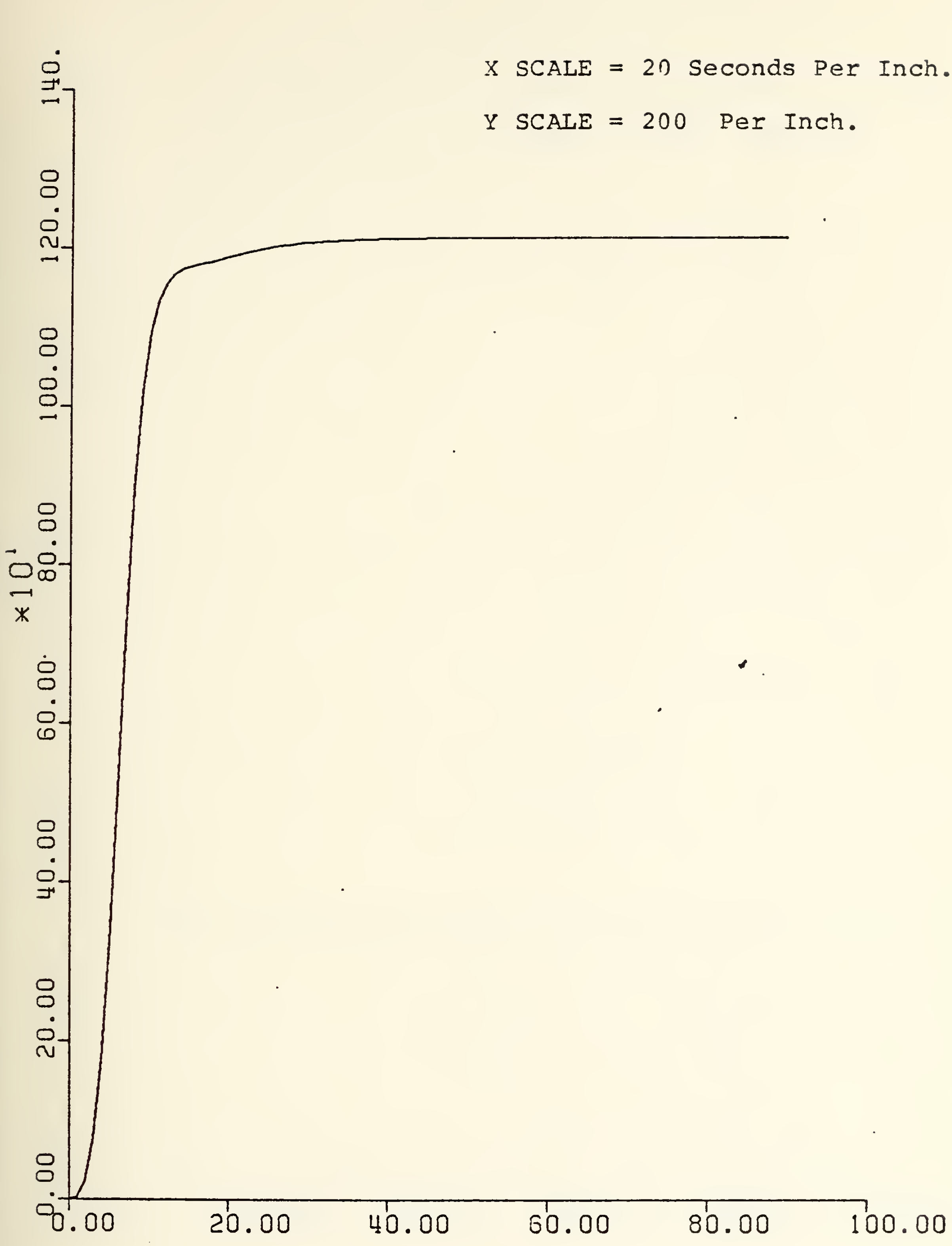


Figure 31. K22 vs. Time. UCK = 15 Knots.
D = 8000, A = 0, E = 10, B = 0, C = 100.

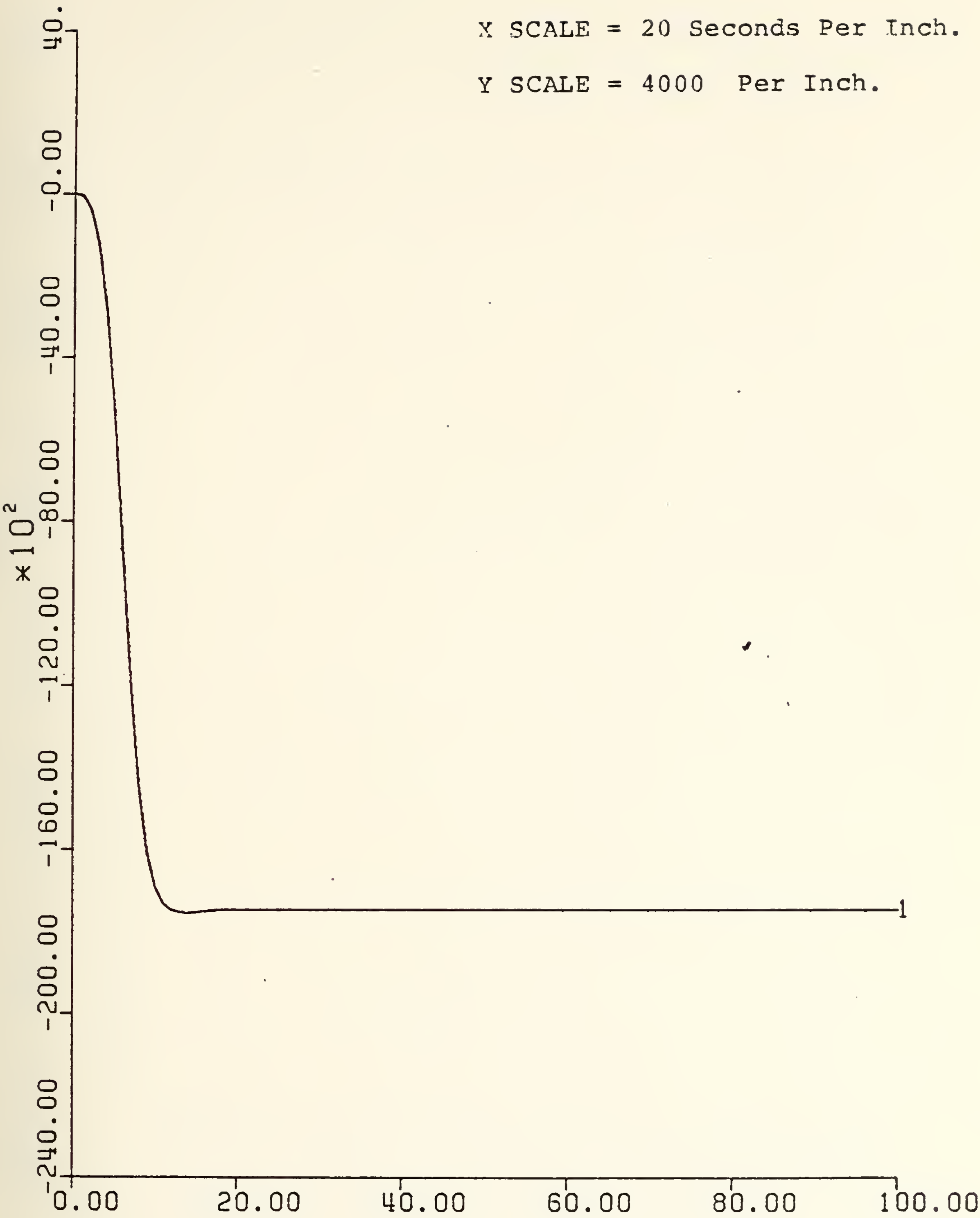


Figure 32. K23 vs. Time. UCK = 15 Knots.
D = 8000, A = 0, E = 10, B = 0, C = 100.

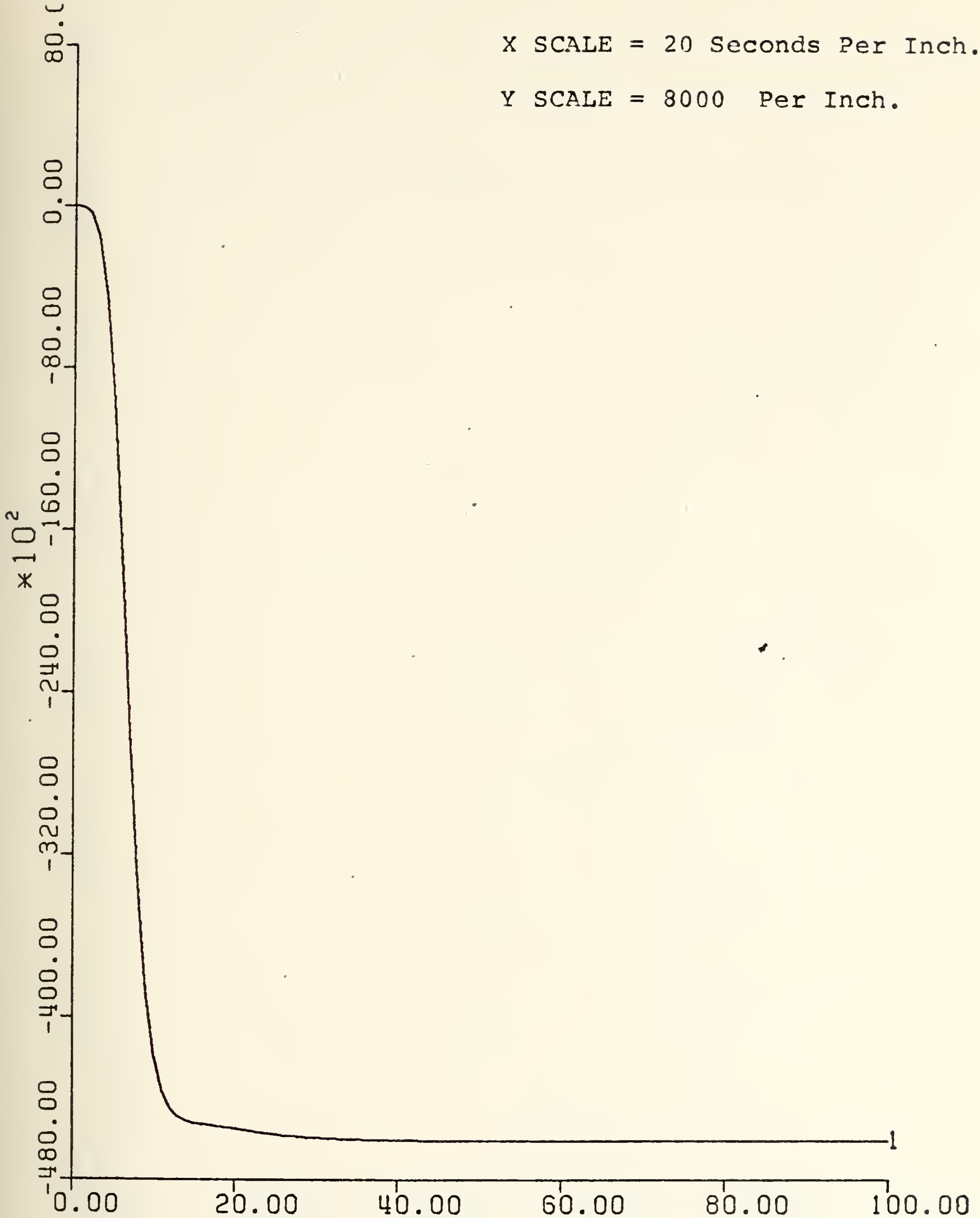


Figure 33. K24 vs. Time. UCK = 15 Knots.
D = 8000, A = 0, E = 10, B = 0, C = 100.

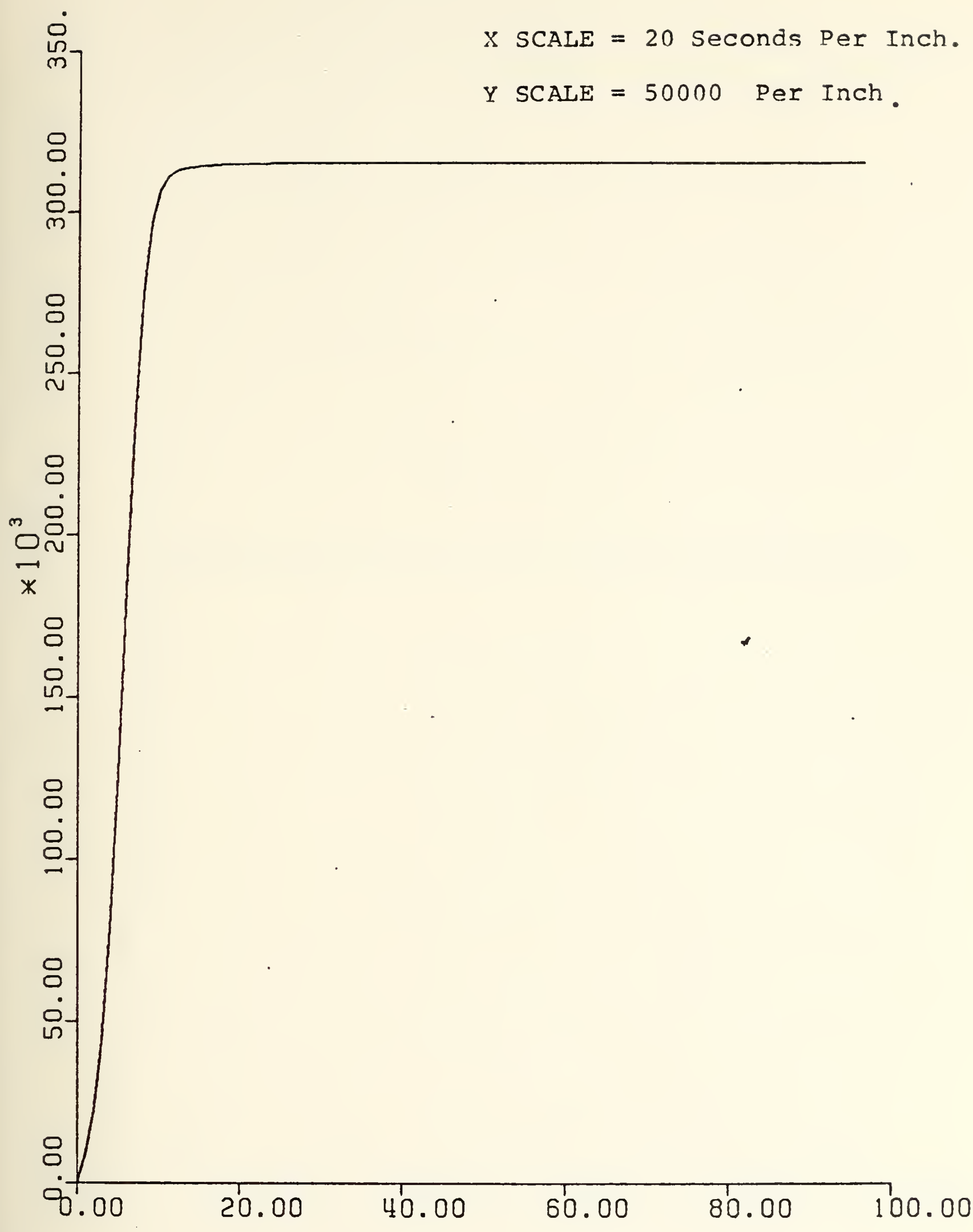


Figure 34. K33 vs. Time. UCK = 15 Knots.
D = 8000, A = 0, E = 10, B = 0, C = 100.

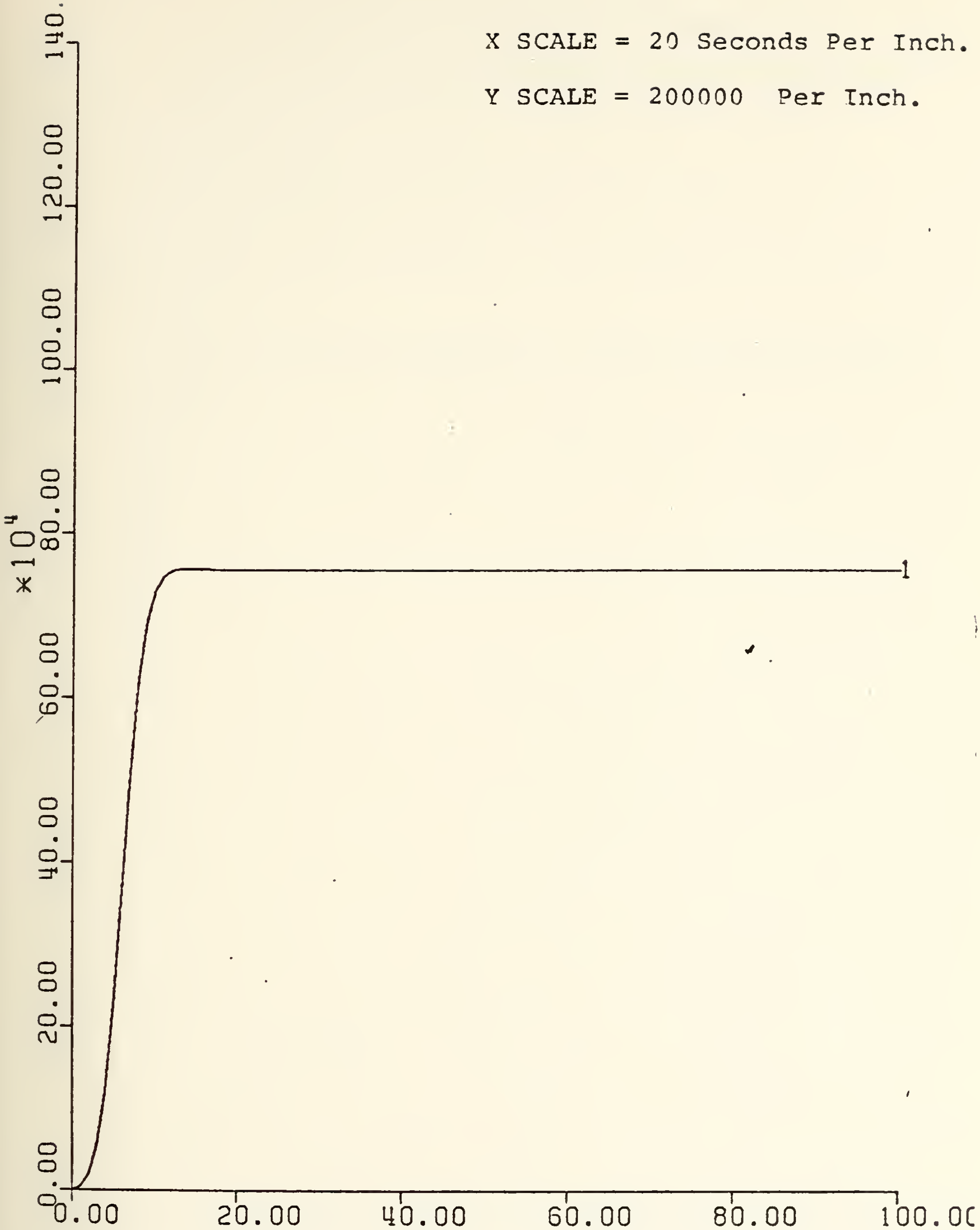


Figure 35. K34 vs. Time. UCK = 15 Knots.
D = 8000, A = 0, E = 10, B = 0, C = 100.

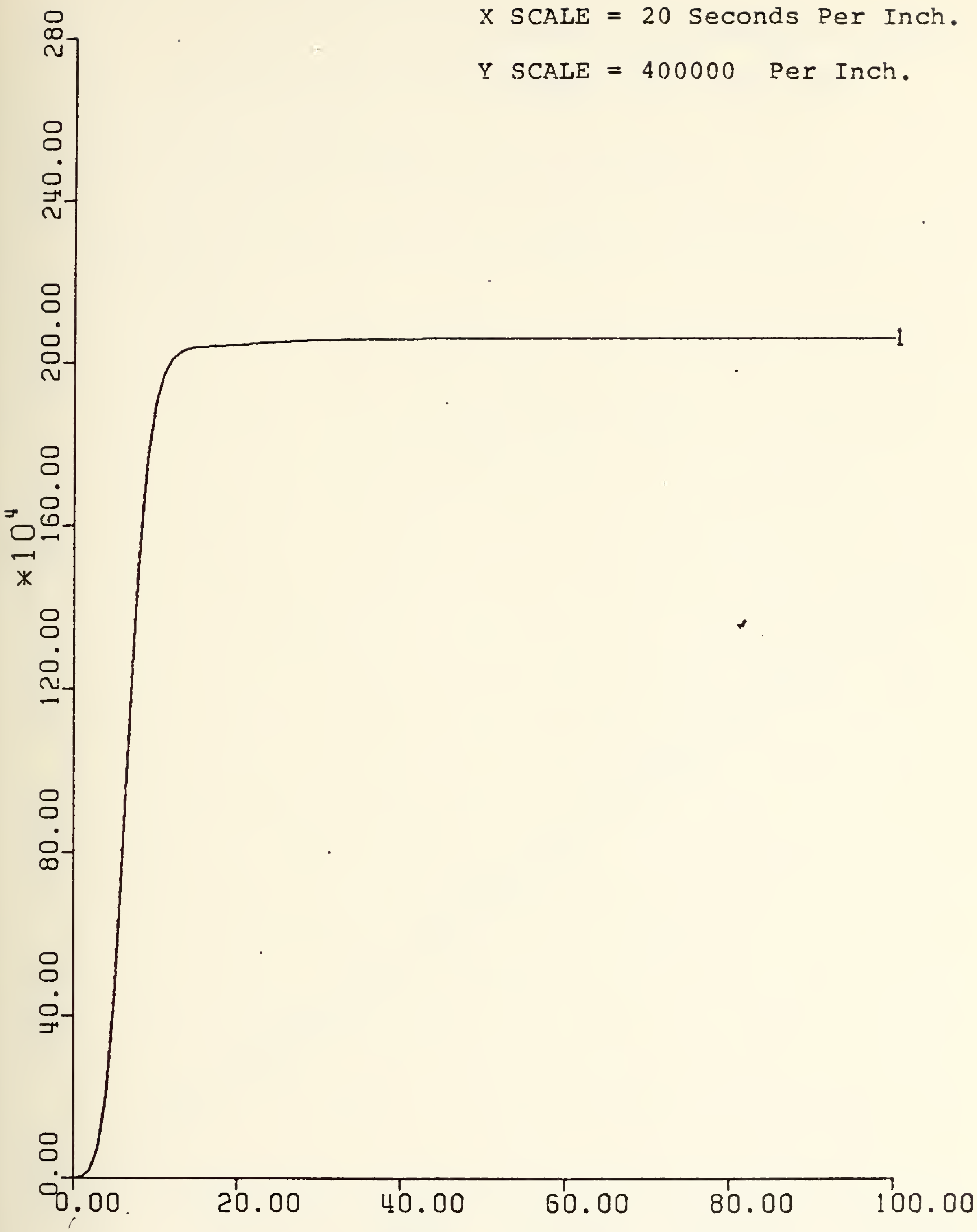


Figure 36. K44 vs. Time. UCK = 15 Knots.
D = 8000, A = 0, E = 10, B = 0, C = 100.

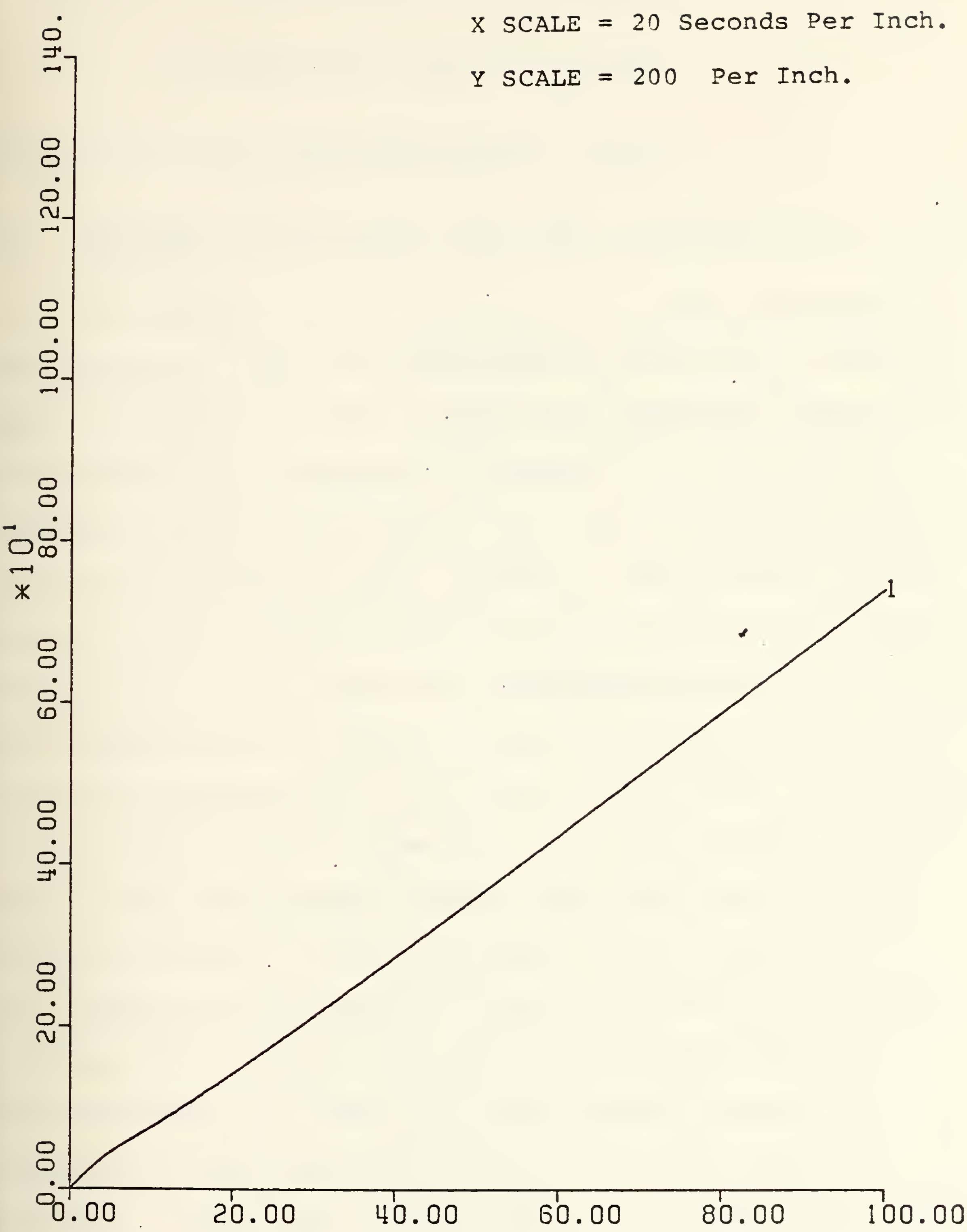


Figure 37. K11 vs. Time. UCK = 15 Knots.
With Transformation Of Depth Rate = W.
D = 8000, A = 0, E = 10, B = 0, C = 100.

$$DSAD = -0.31623*ZOER-26.38/_{UK}*ZODOT + 36.069*PERR + 1539.45/_{UK}*P1DOT$$

where UK is the instantaneous speed (knots).

B. AUTOMATIC DEPTH-PITCH CONTROLLER AND SIMULATION OF THE RESULTS

The feedback gains, which are the optimal solution of the linearized vertical plane equations must be put into the general controller schema in which the submarine dynamics are represented in six degrees of freedom (i.e., non-linear equations of motion). Because only the simulation of this can justify the validity of the solution. The complete modified version of the Drurey's depth and pitch controller is shown in Fighre 38. As it is shown the sternplane controller (actuator) was not designed as a part of the controller and put into the controller separately with the plane rate 7^{o}/sec. The dynamics of the actuator is the same as Drurey's and Stamps' controller used. The same actuator dynamics also was used in the roll controller which is to be discussed in the following section. The actuator block diagram is shown in Figure 39. To preclude stability which occurs as a result of the excessive uses of the sternplane and avoid use of the control surface with big deflections the limiter was put into the pitch and depth error channels. Pitch error limiter was 10^{o} and depth error limiter was 20 feet and found by a trial and error process.

After the completion of the controller design, various tests were run to see the effect of the pitch and depth controller on depth, pitch, roll and sternplane responses.

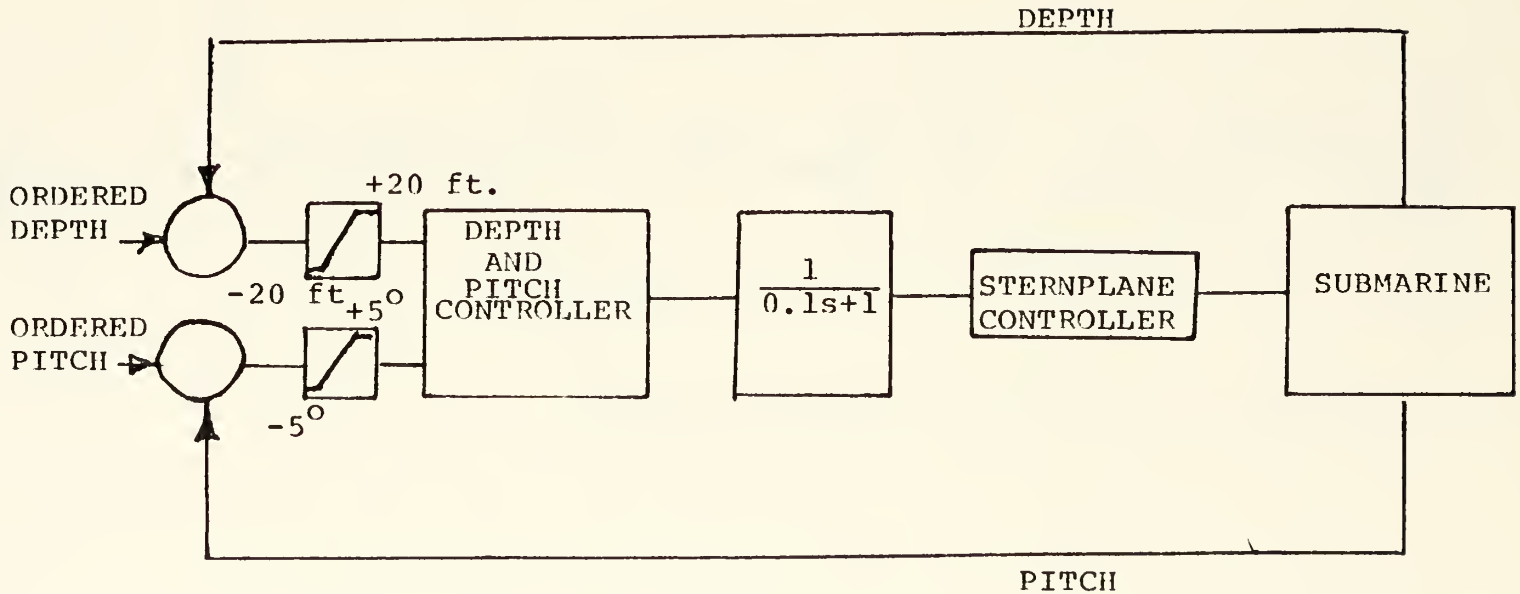


Figure 38. Depth And Pitch Controller.

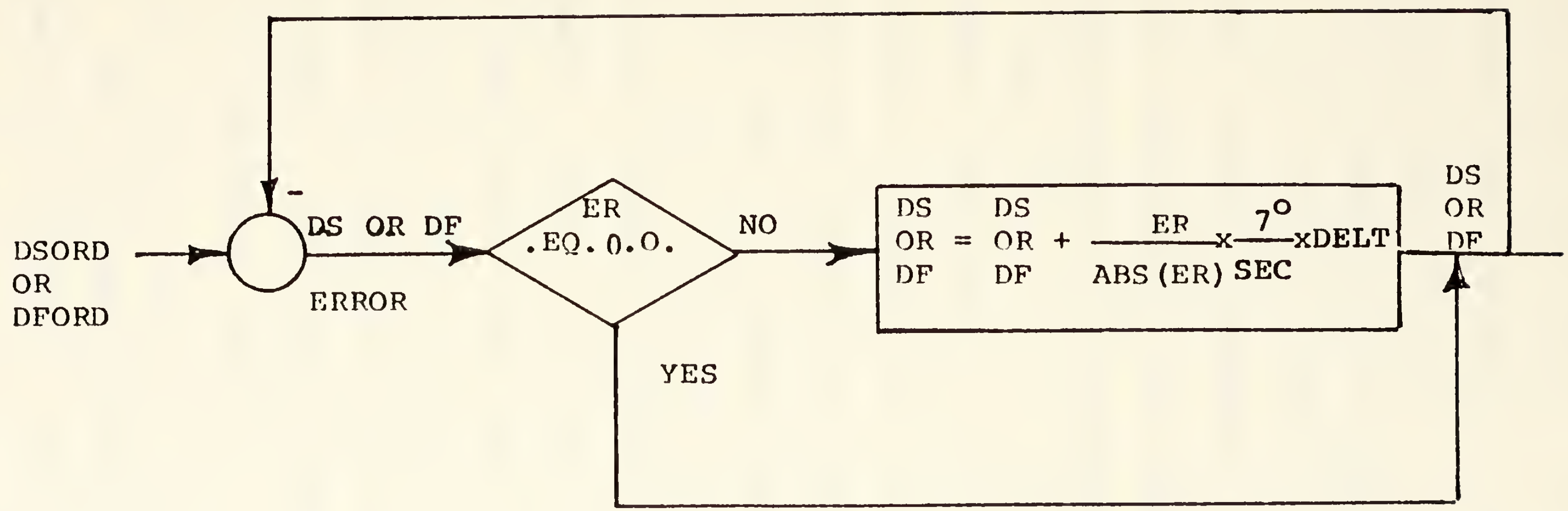


Figure 39. Hydraulic Actuator Model For Stern And Fairwater Planes. (DS Refers To Stern Planes Actuator. DF Refers to Fairwater Planes Actuator).

The results of tests at 6, 12, 18, and 24 knots to a constant 35° left rudder angle are shown in Figures 40 through 55. When these results are compared with the responses of the ship with no pitch and depth controller which is shown in Figures 3 through 6 at 24 knots and in Figures 8 through 25 at 18, 12, and 6 knots. The following comparisons can be drawn:

1. At 12 and 18 knots controller kept the ship's depth and pitch stable after very reasonable transient time. The steady state pitch and depth are $(5.2)^{\circ}$ - (9.2) feet at 12 knots and $(4.7)^{\circ}$ - (9) feet at 18 knots.
2. At 6 knots, the controller failed to keep the pitch and depth stable. The ship very slowly kept on losing depth. The reason was insufficient speed scaling of the feedback gains and needs for another control surface (Fairwater planes). Lack of fairwater plane control surface in the depth-pitch controller unabled it to keep ship stable at low speeds. But in this thesis the primary concern was to minimize the snap roll which occurs at high speed. In Reference 2 Stamps collected data which shows the peak snap roll as a function of the approach speed and ordered rudder angle. This data is repeated at the following page for convenience (Table I). It is seen that dangerous snap roll starts occuring at approach speeds above 12 knots. For this reason unability of the controller at low speed was neglected. Because, a control scheme, which at low speed uses Drury's original depth-pitch controller (Fairwater plane is part of controller) and at high

speed uses this design (Fairwater plane is not a part of depth-pitch controller but is a part of the roll controller) can be designed and switching from one to another can be achieved.

3. At 24 knots the controller again failed to keep the ship stable. Depth and pitch response went into oscillation with big amplitudes. Original roll response of the ship which is shown in Figure 5 was destroyed in the sense of decreasing amplitudes of roll oscillation. It did not reach stable value and appeared to be oscillating in the range of 10°. The reason was the following. The big snap roll which was around 37°, initially gave very big disturbance and oscillation. With these big disturbances the controller which uses only the sternplane as a control surface was unable to do the job. It was thought that, if there had been any controller which could have decreased the snap roll (Roll controller) it would have been able to stabilize the ship in pitch and depth as well as in the roll response.

Based on the results of these tests, proceeding with the roll controller design which would make use of fairwater plane as a control surface was decided.

TABLE I

PEAK SNAP ROLL ANGLE (DEGREES) VS. APPROACH SPEED (KNOTS) AS A FUNCTION OF ORDERED RUDDER ANGLE (DEGREE)

SPEED (KNOTS) RUDDER	4	8	12	16	20	24
1	0.15	0.66	1.45	2.58	4.03	5.83
2	0.24	0.99	2.22	3.95	6.18	8.88
3	0.31	1.24	2.80	5.00	7.84	11.28
4	0.37	1.45	3.29	5.87	9.26	13.27
5	0.41	1.63	3.71	6.71	10.32	15.72
6	0.45	1.80	4.04	7.39	11.65	17.90
7	0.49	1.93	4.46	7.93	13.11	19.87
8	0.52	2.09	4.81	8.36	14.47	21.64
9	0.55	2.22	5.12	9.10	15.72	23.23
10	0.58	2.33	5.38	9.88	16.88	24.65
11	0.60	2.42	5.60	10.62	17.96	25.94
12	0.63	2.50	5.78	11.31	18.95	27.13
13	0.65	2.60	5.94	11.97	19.86	28.20
14	0.67	2.72	6.06	12.58	20.71	24.17
15	0.68	2.83	6.33	13.17	21.49	30.04
16	0.70	2.92	6.65	13.72	22.20	30.83
17	0.72	3.01	6.96	14.23	22.87	31.57
18	0.74	3.09	7.25	14.72	23.48	32.22
19	0.76	3.16	7.54	15.16	24.04	32.81
20	0.77	3.22	7.80	15.59	24.55	33.34
21	0.78	3.27	8.06	15.98	25.02	33.82

SPEED (KNOTS) RUDDER	4	8	12	16	20	24
22	0.79	3.32	8.30	16.34	25.45	34.25
23	0.80	3.36	8.52	16.68	25.84	34.64
24	0.81	3.39	8.74	16.99	26.20	34.99
25	0.82	3.42	8.95	17.28	26.51	35.30
26	0.83	3.44	9.14	17.55	26.80	35.57
27	0.84	3.46	9.32	17.79	27.06	35.81
28	0.86	3.47	9.49	18.01	27.29	36.02
29	0.87	3.48	9.65	18.22	27.50	36.20
30	0.87	3.49	9.80	18.40	27.68	36.36
31	0.88	3.49	9.94	18.57	27.84	36.50
32	0.89	3.51	10.06	18.71	27.97	36.60
33	0.89	3.58	10.18	18.85	28.09	36.68
34	0.90	3.64	10.29	18.96	28.19	36.75
35	0.90	3.70	10.39	19.06	28.27	36.80

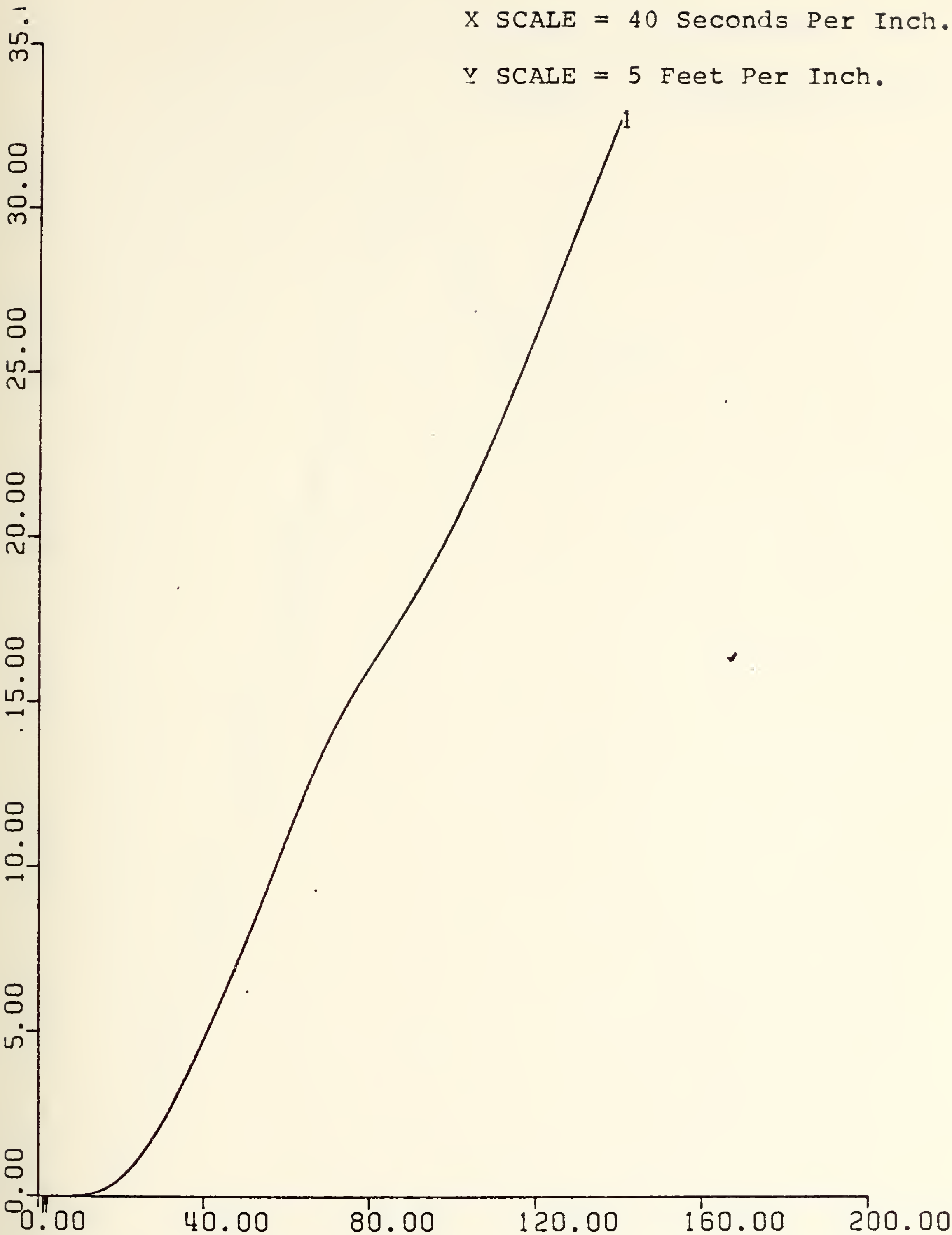


Figure 40. Depth vs. Time. With Depth-Pitch Controller. UCK = 6 Knots. Rudder Ordered = 35°.

Figure 41. Pitch vs. Time. With Depth-Pitch Controller. UCK = 6 Knots. Rudder Ordered = 35°.

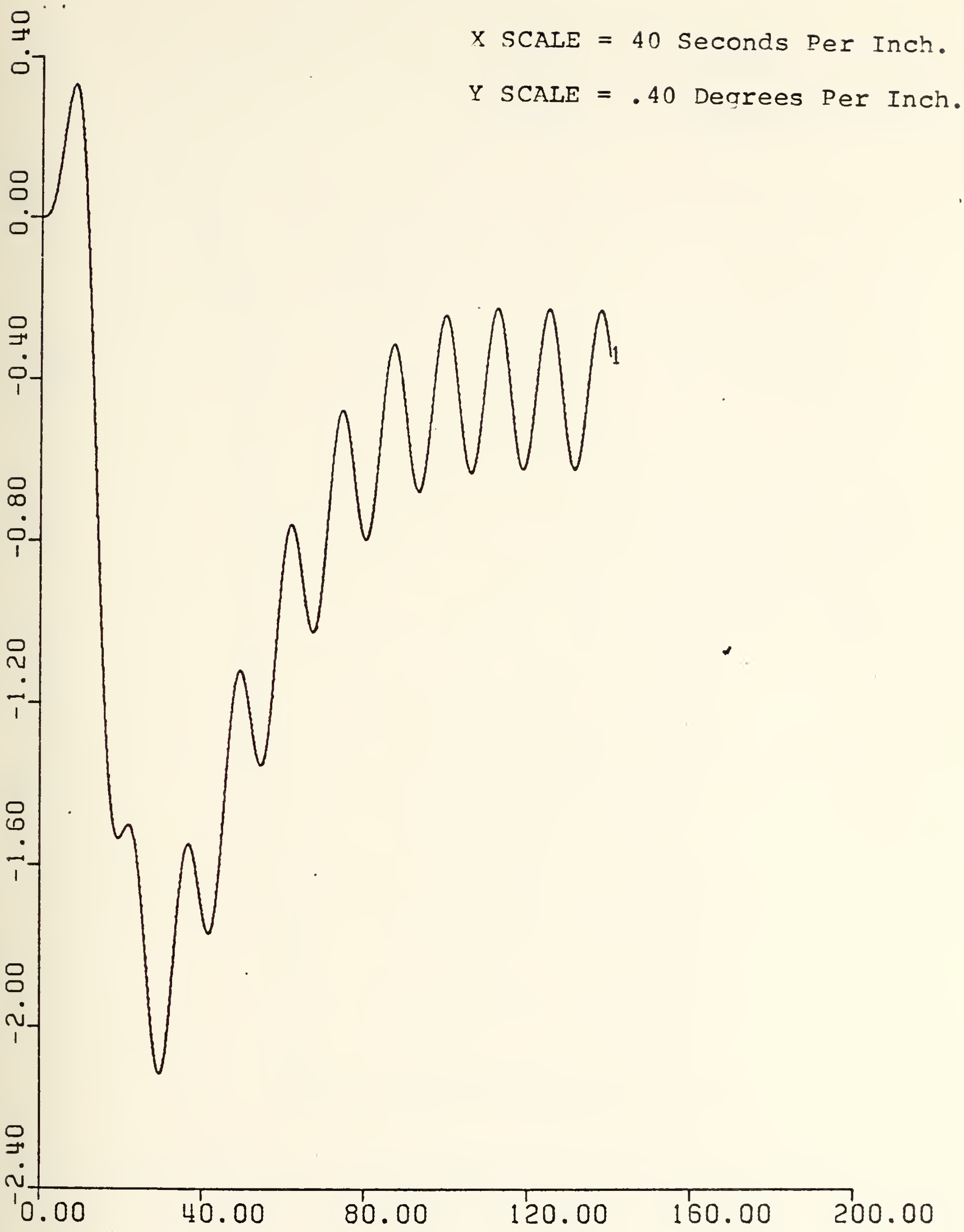


Figure 42. Roll vs. Time. With Depth-Pitch Controller. UCK = 6 Knots. Rudder Ordered = 35°.

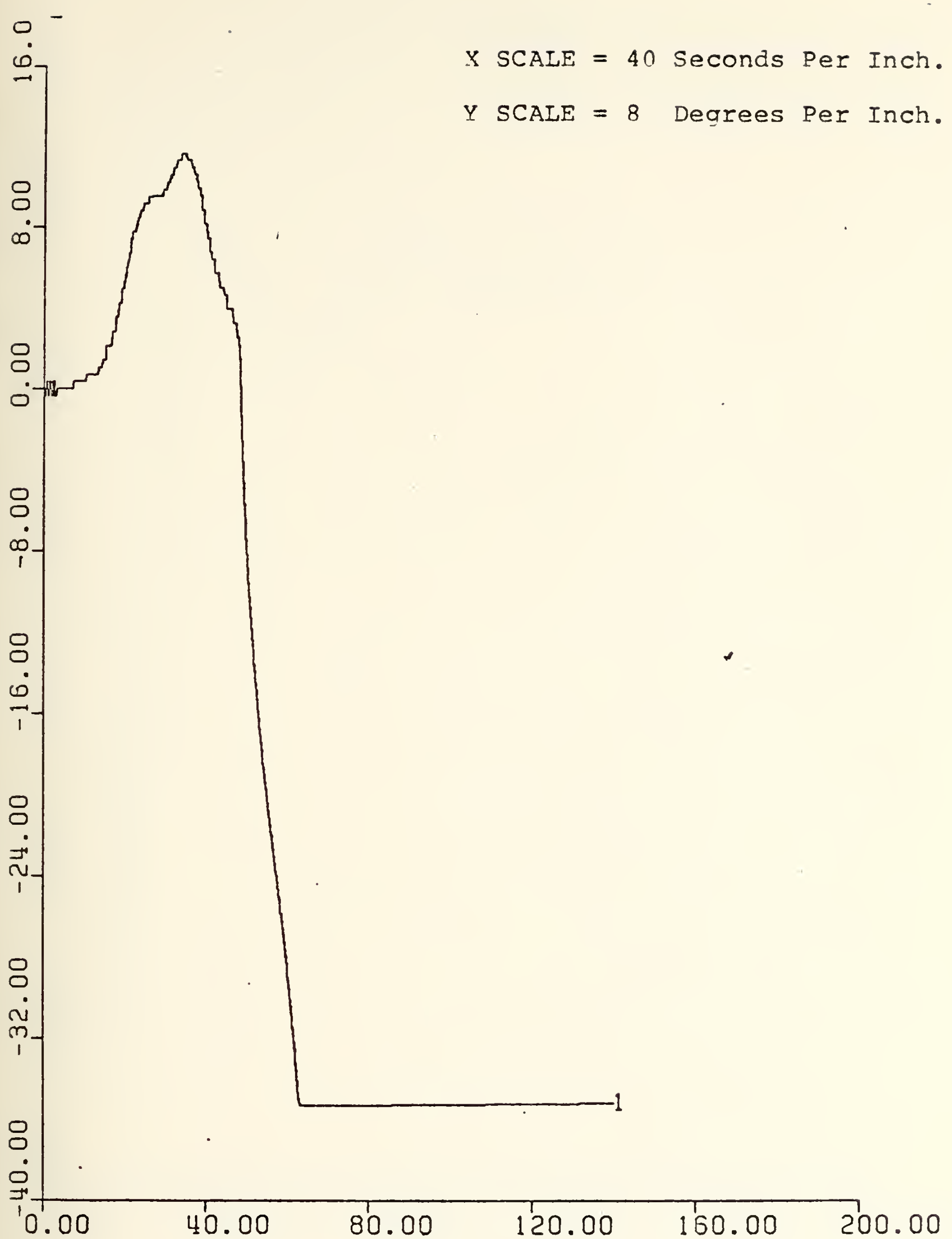


Figure 43. Sternplane Angle vs. Time. With Depth-Pitch Controller. UCK = 6 Knots. Rudder Ordered = 35°.

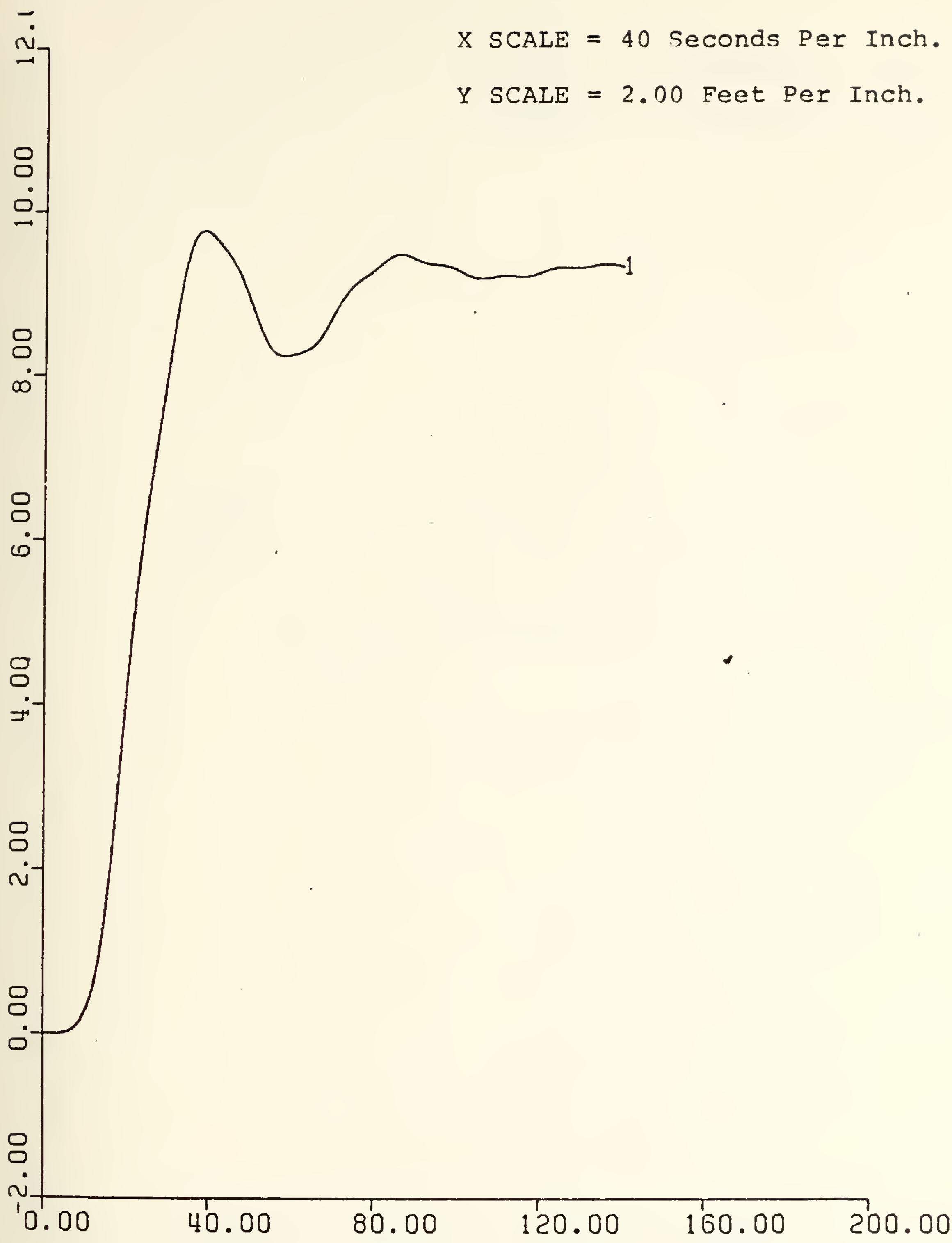


Figure 44. Depth vs. Time. With Depth-Pitch Controller. UCK = 12 Knots. Rudder Ordered = 35°.

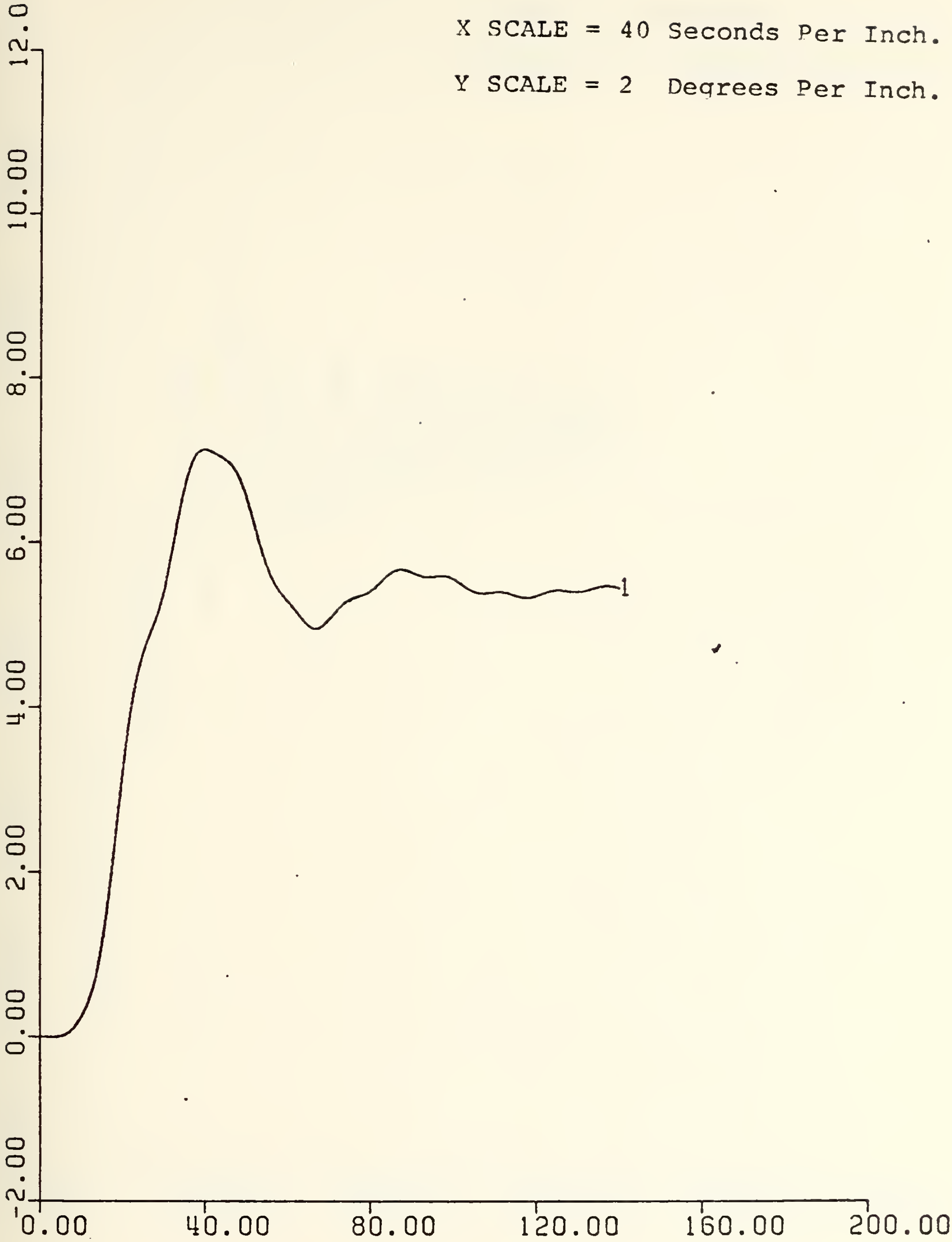


Figure 45. Pitch vs. Time. With Depth-Pitch Controller. UCK = 16 Knots. Rudder Ordered = 35°.

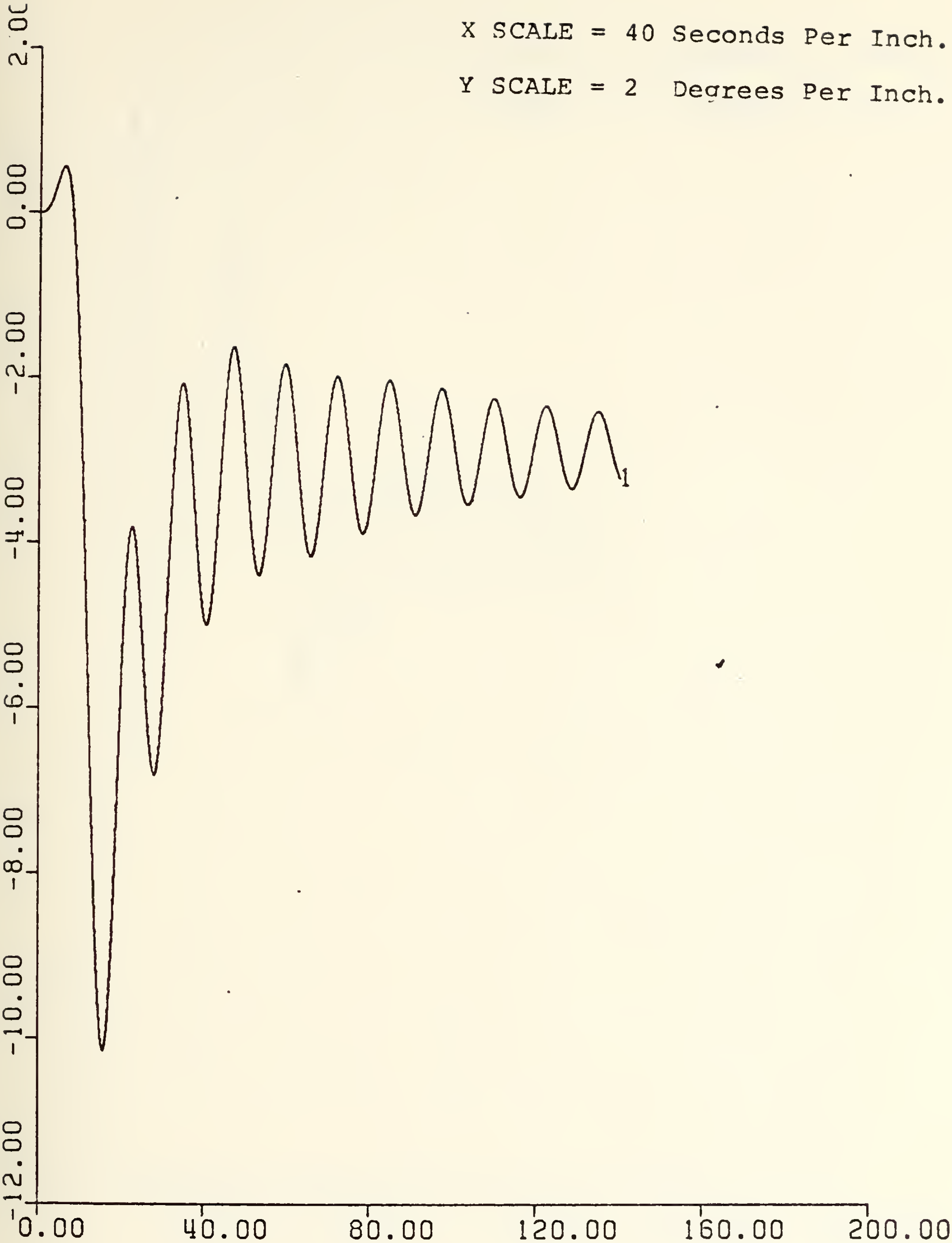


Figure 46. Roll vs. Time. With Depth-Pitch Controller. UCK = 12 Knots. Rudder Ordered = 35°.

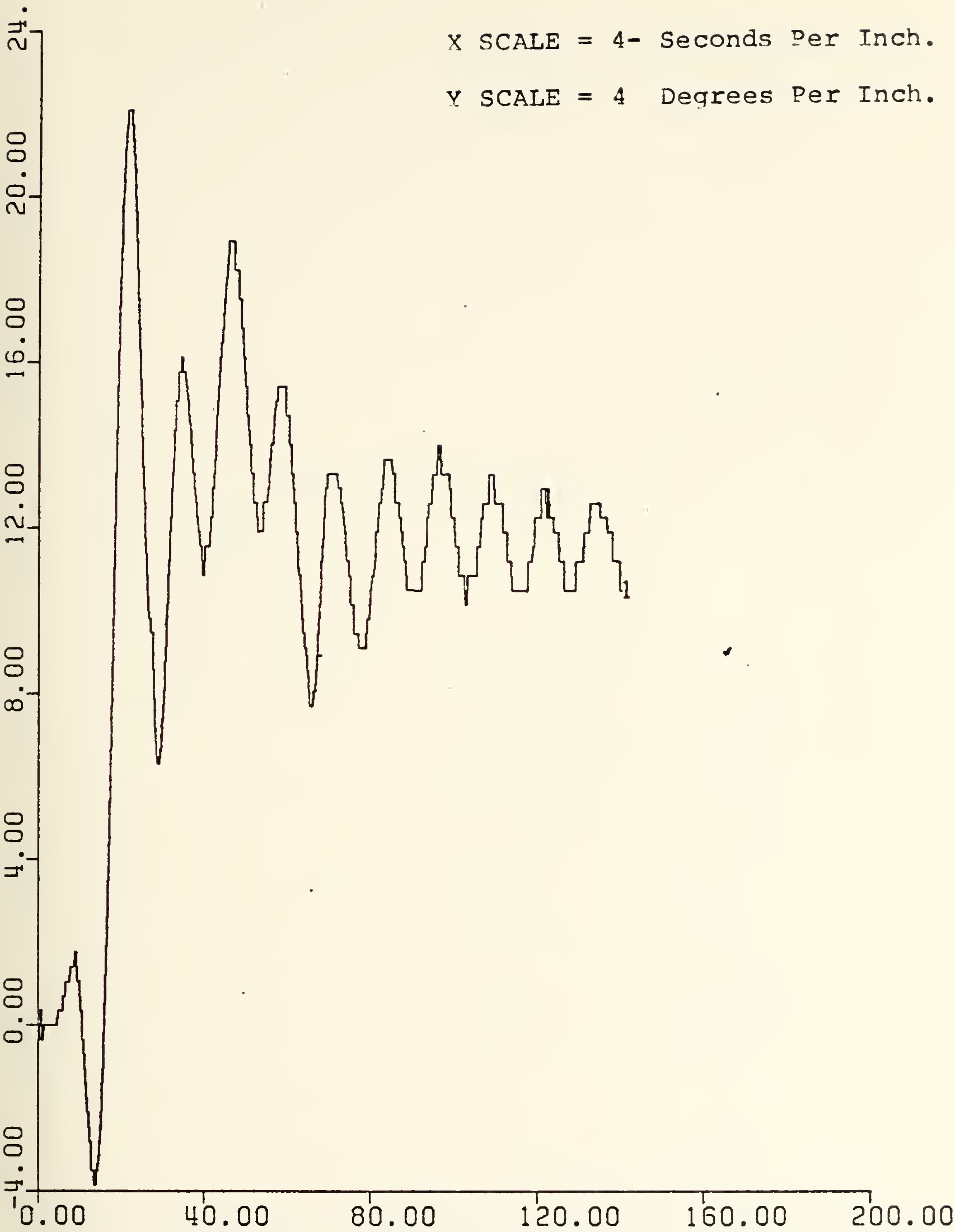


Figure 47. Sternplane Angle vs. Time. With Depth-Pitch Controller. UCK = 12 Knots. Rudder Ordered = 35°.

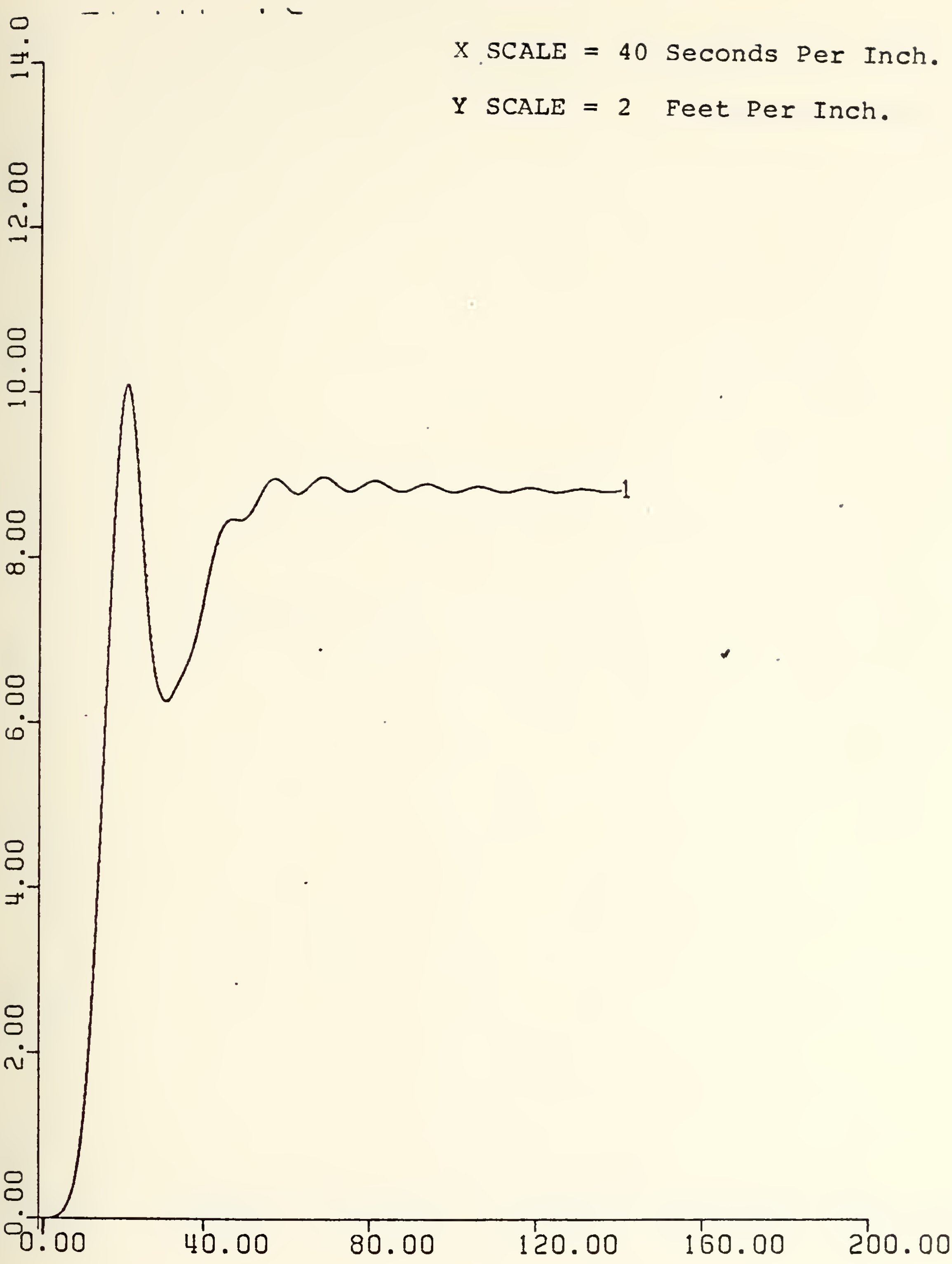


Figure 48. Depth vs. Time. With Depth-Pitch Controller.
UCK = 18 Knots. Rudder Ordered = 35°.

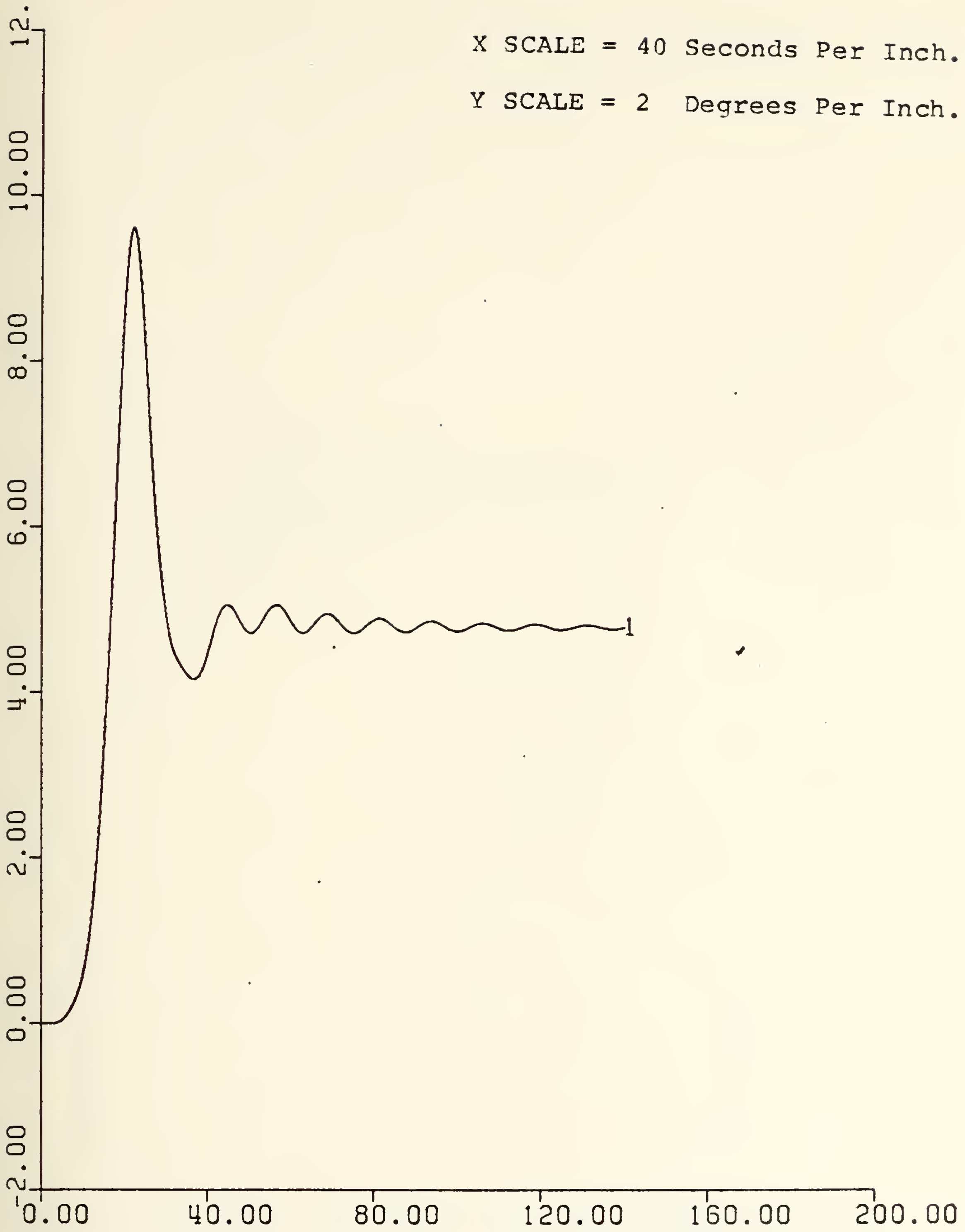


Figure 49. Pitch vs. Time. With Depth-Pitch Controller. UCK = 18 Knots. Rudder Ordered = 35°.

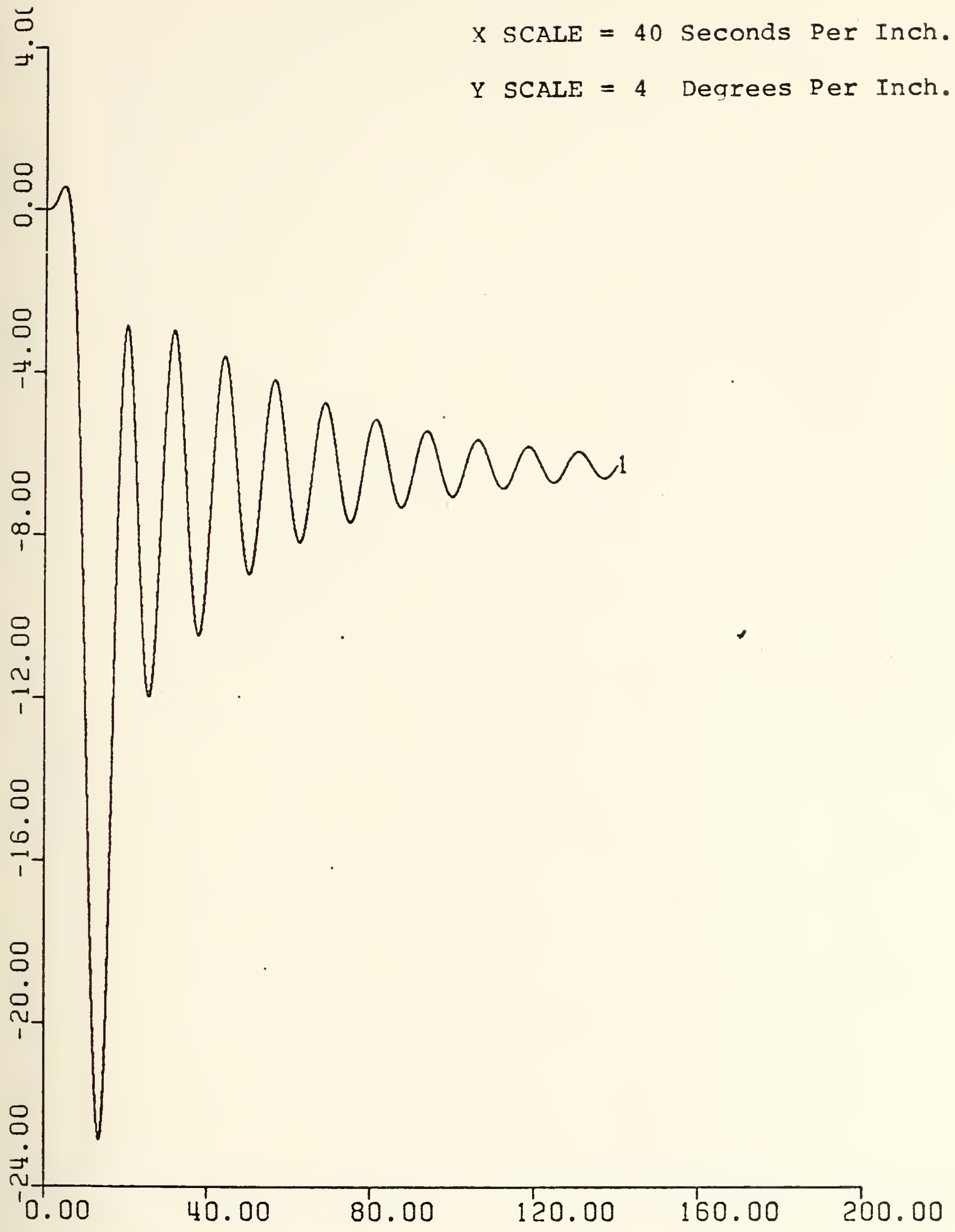


Figure 50. Roll vs. Time. With Depth-Pitch Controller, UCK = 18 Knots. Rudder Ordered = 35°.

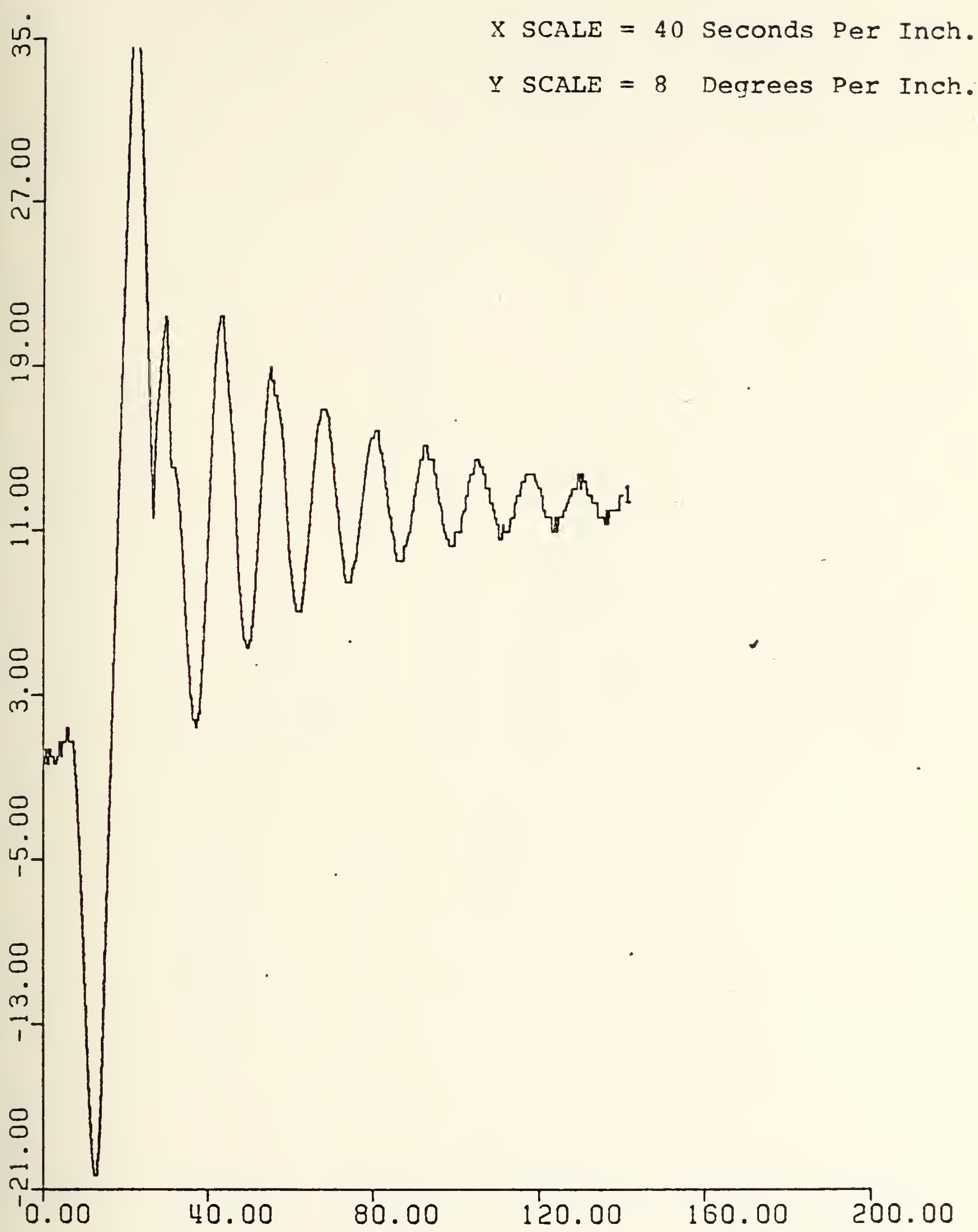


Figure 51. Sternplane Angle vs. Time. With Depth-Pitch Controller. UCK = 18 Knots. Rudder Ordered = 35°.

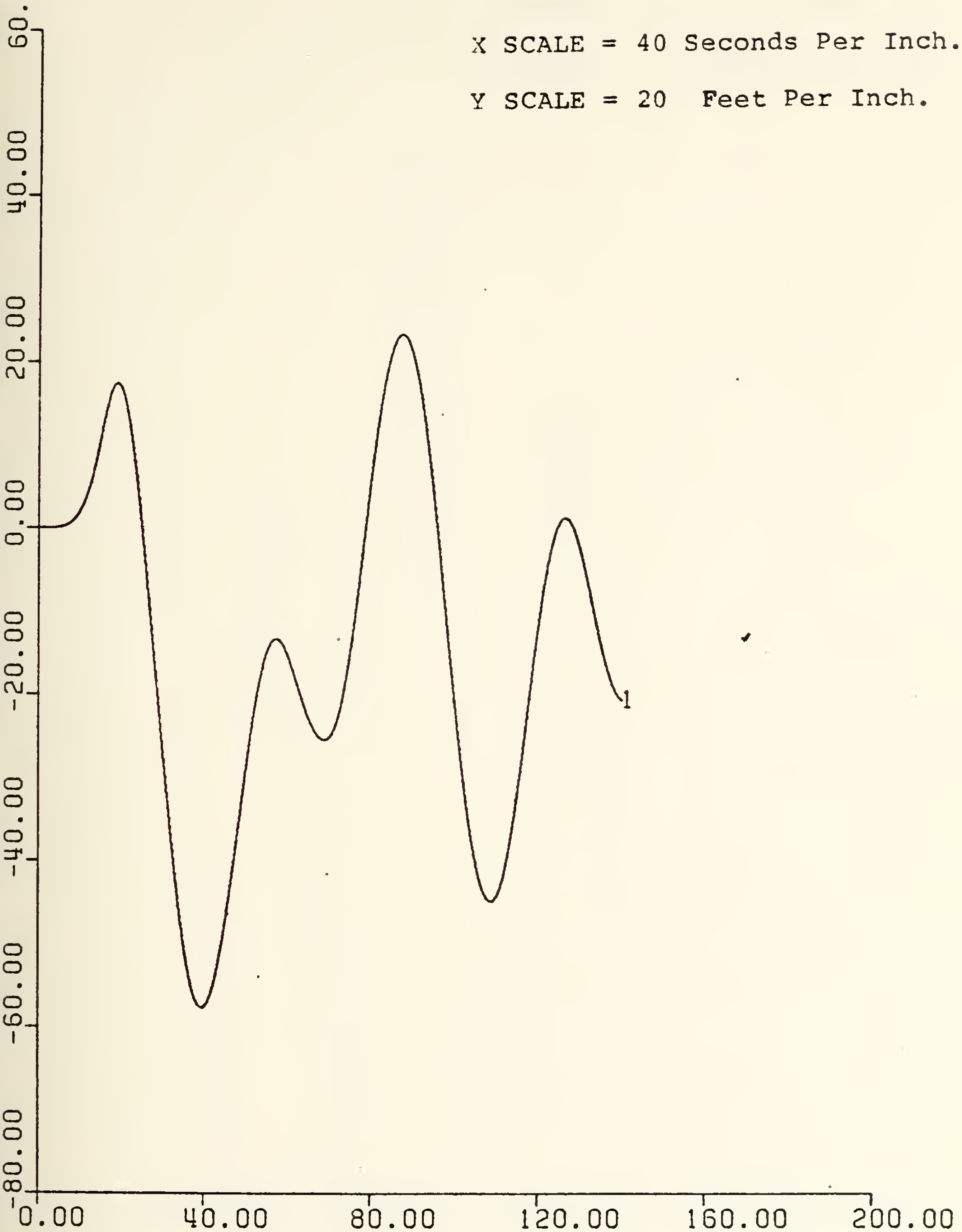


Figure 52. Depth vs. Time. With Depth-Pitch Controller.
UCK = 24 Knots. Rudder Ordered = 35°.

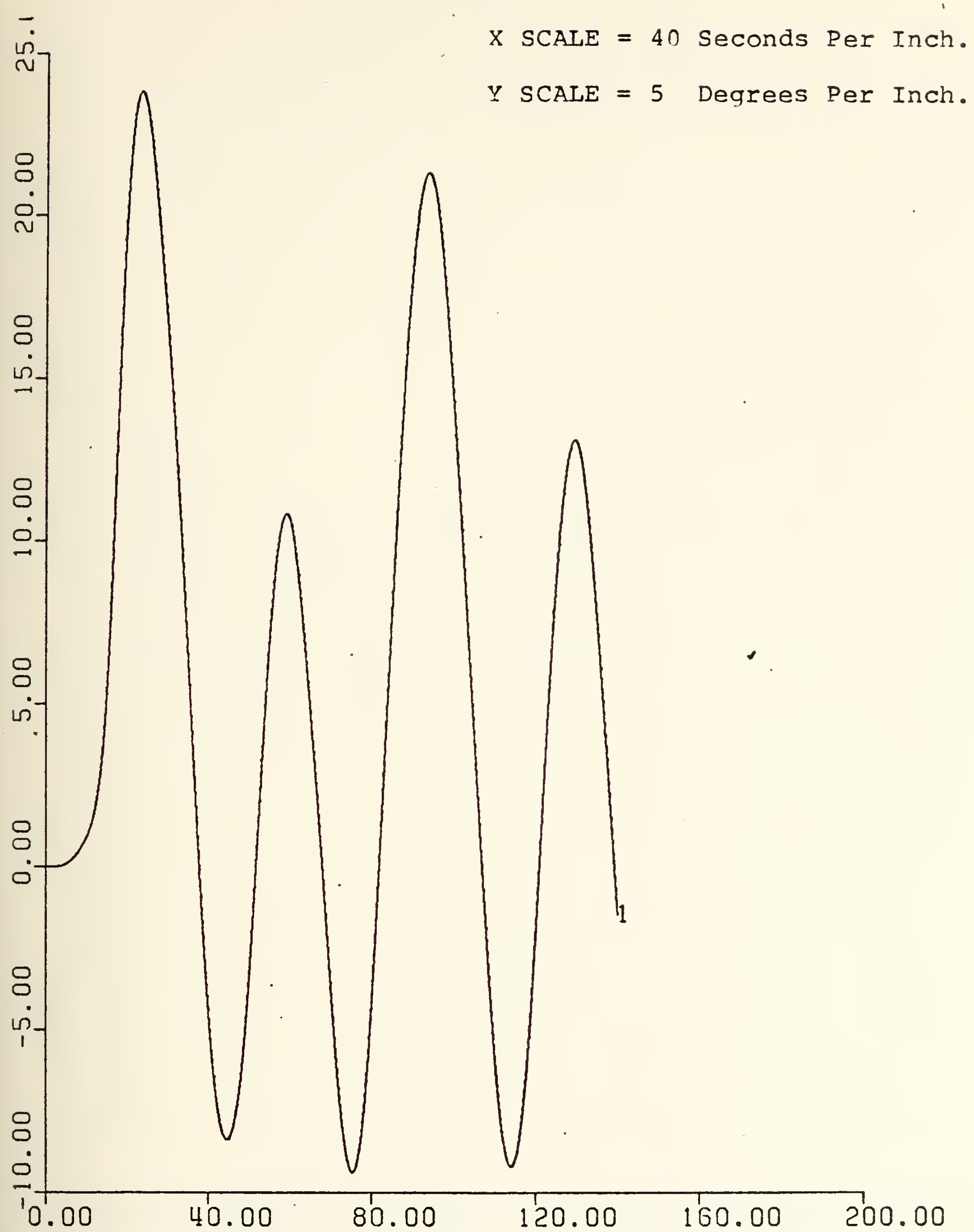


Figure 53. Pitch vs. Time. With Depth-Pitch Controller. UCK = 24 Knots. Rudder Ordered = 35°.

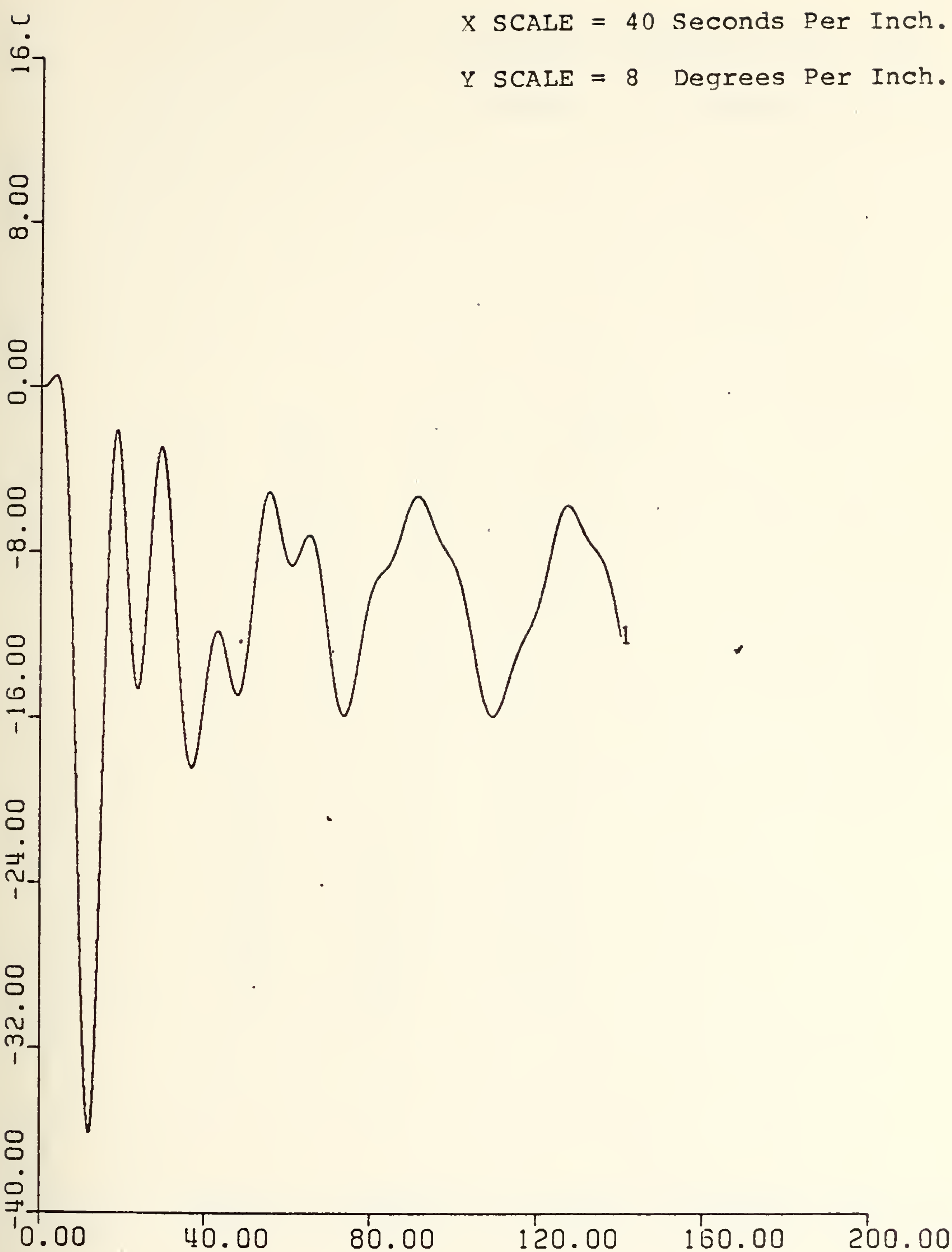


Figure 54. Roll vs. Time. With Depth-Pitch Controller.
UCK = 24 Knots. Rudder Ordered = 35°.

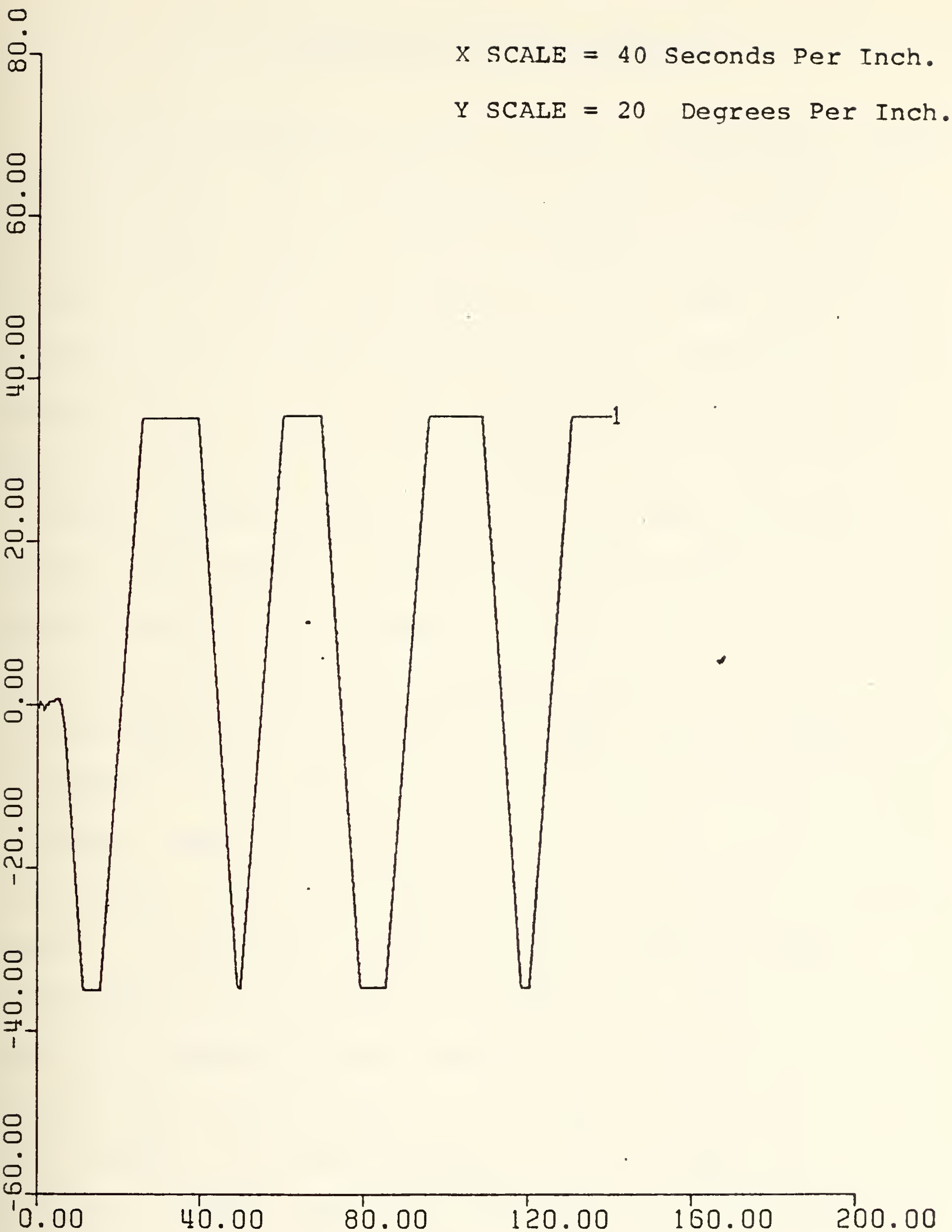


Figure 55. Sternplane Angle vs. Time. With Depth-Pitch Controller. UCK = 24 Knots. Rudder Ordered = 35°.

V. AUTOMATIC ROLL CONTROLLER

In the introduction of the thesis, the possible choices of controlling roll was discussed briefly and stated that fairwater planes were to be used as control fins to control the roll. The reason that brought up this idea lies behind the needs of more control surface than was available in the present design criteria. Roll control of a high speed submarine has continued to be a problem over the years because of limited control surface. Control engineers have been restricted using rudder, stern and fairwater plane. All of the control surface was not meant to control roll. In the present design criterias stern and fairwater planes are meant to control the submarine in the vertical plane motion (depth-pitch). The rudder has been used as a part of course controlling of the ships. Among the three control surfaces, rudder is the only one that has direct correlation with the submarines roll angles. In the latest study, which was done by Stamps [Reference 2], it was used to control roll. The concept of Stamps roll controller was based on the idea of adjusting the initial rudder angle order as a function of the integral of error between the allowed maximum roll and actual roll angles. The initial rudder order was chosen such that the peak roll expected for a given approach speed would be less than the maximum allowed roll. The integral of roll error was then computed and scaled to represent and additive term applied to

the initial rudder order. Stamps design didn't give any structural changes to the present navy submarines design criteria. In a sense of simplicity it was perfect. But it prohibited using hard and excessive rudder order which is highly desirable at some submarines required maneuvering in certain tactical areas. Since the Stamps design slowed down the yaw rate and caused the ship to change its course very slowly, alternative design ways were investigated and using fairwater plane in the differentially deflected mode was chosen as a possible improvement.

The concept of roll control by means of fairwater planes is based on the idea of deflecting the fairwater plane differentially such that it can give a roll moment in opposite direction to the instantaneous roll angle. If the ship has a roll angle to starboard side, the planes are to be deflected to give a roll moment to portside. The positive sense of this additional roll moment created by the differentially deflected sailplanes is the same as of Reference 5. The positive sense of sailplane deflection angle adopted in this thesis (positive for port sailplane deflected leading edge up, starboard sailplane deflected leading edge-down) is in agreement with that used for other control surfaces in Reference 5: Positive when the surfaces are deflected in such a direction as to increase the relevant angle of the submarine about its mass center. In the case of differentially deflected sailplanes, the angle is the roll angle and this is defined in Reference 5 to be positive starboard side down.

Since, in the present design criteria of navy submarines, sailplanes are not used in a differentially deflected mode, standard equations of motion which are developed by NSRDC in Reference 5, do not have correlative terms which take the additional moment term, created by the sailplanes into account. For this reason, before starting to design the roll controller, this additive moment must be estimated. Once the counter moment is found it can be placed in the righthand side of the roll moment equation.

A. ESTIMATING ROLL MOMENT DUE TO DIFFERENTIALLY DEFLECTED SAILPLANES

In vertical plane motion, the normal force due to the fairwater planes (sailplanes) is given by the equation of

$$F_N = \frac{\rho}{2} L^2 u^2 \cdot Z_{\delta b} \cdot \delta b$$

Where ρ = 2

L = ship length in feet

U = forward speed

$Z_{\delta b}$: hydrodynamic coefficient associated with the sailplane deflection (in conventional mode - right and left side moves together in the same direction).

δb = Deflection of the sailplane in radians.

After setting $\rho = 2$ the normal force equation becomes

$$F_N = L^2 \cdot U^2 \cdot Z_{\delta b} \cdot \delta b$$

This force is due to both sides of the sailplanes. The force due to one side of the plane pair is half of the total

force that is $\frac{1}{2} L^2 \cdot U^2 \cdot Z_{\delta b} \cdot \delta b$. If both sides of the planes are deflected by the same amount and in opposite direction compared to each other, this configuration creates a moment associated with the moment arm between these opposite forces. This is shown in Figure 56. Total amount of the moment due to sailplanes can be written

$$M = 2 * \frac{1}{2} \cdot L^2 \cdot U^2 \cdot Z_{\delta b} \cdot \delta b \cdot \text{(moment arm)}$$

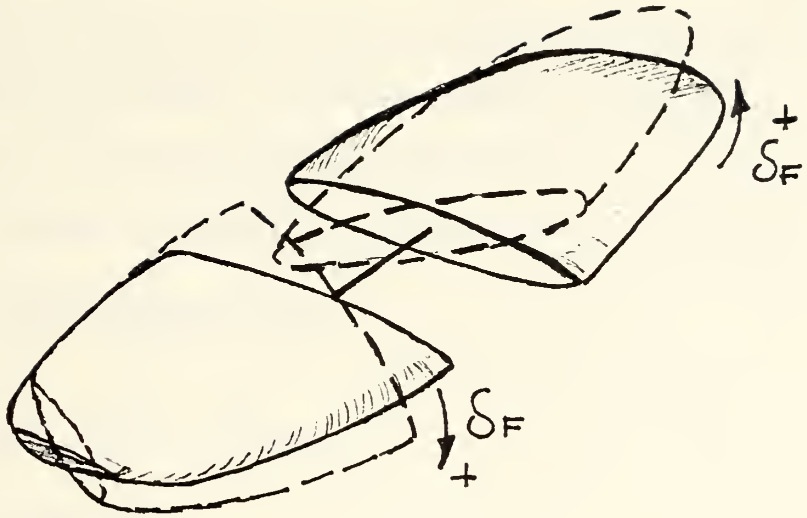
$$M = L^2 \cdot U^2 \cdot Z_{\delta b} \cdot \delta b \cdot \text{(moment arm)} \cdot \frac{L}{L}$$

$$= L^3 \cdot U^2 \cdot \delta b \cdot (Z_{\delta b} \cdot \text{moment arm})/L$$

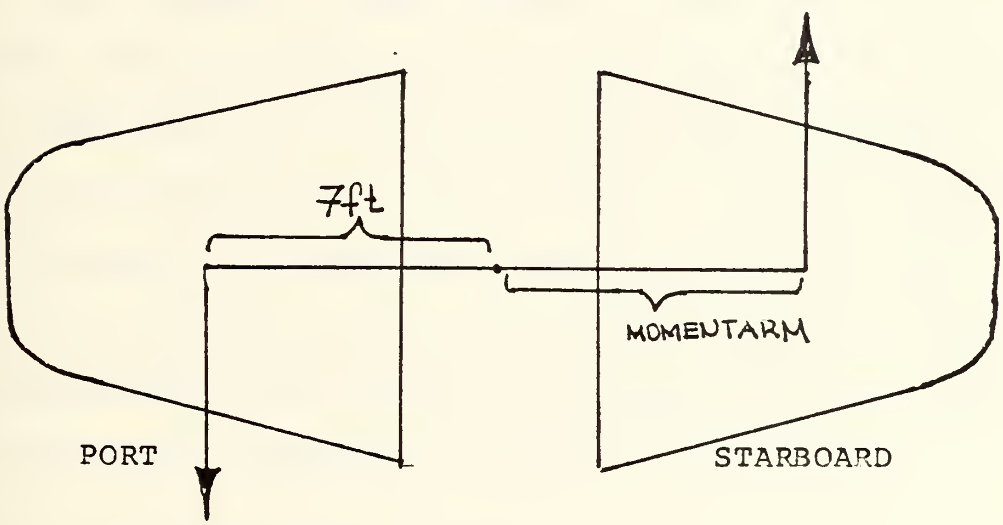
if this momemt term is placed in the right side of the equation of motion about the body axis system X-Axis (roll axis), the complete equation takes the form of

$$
\begin{aligned}
I_X \dot{p} + (I_X - I_Y) qr = {} & L^5 \left[K\dot{p}' \dot{p} + Kqr'qr + K\dot{r}'\dot{r} + K_{p|p|}' p|p| \right] \\
& + L^4 \left[Kp'up + Kr'ur + K_{\dot{v}}'\dot{v} + K_{wp}'wp \right] \\
& + L^3 \left[K_*'u^2 + K_v'uv + K_{v|v|}'v \left|(v^2 + w^2)\right|^{1/2} \right] \\
& + L^3 K_{vw}'vw + L^3 \cdot U^2 \cdot K_{\delta r} \cdot \delta r \\
& + L^3 \cdot U^2 \cdot (Z_{\delta b} \cdot \text{moment arm})/L \cdot \delta_F \\
& + B_{ZB} \text{ Sin } \text{ Cos }
\end{aligned}
$$

In this last form δb is replaced by δ_F to indicate that the fairwater plane is to be used in differentially deflected mode (δb represents deflection angle of fairwater plane in conventional usage. Both right and left sides move in the same direction).



-1-



-2-

Figure 56.1. Positive Direction Of Differentially Deflected Sailplanes.
.2. Negative Direction Of Rolling Moment.

The moment arm used in this study was estimated by invoking the data from Reference 6 that belongs to the unclassified fictitious submarine. In the reasonable proportion to the length of the ship, the moment arm was chosen as 7 ft. and, according the data, it was thought acceptable.

If the new hydrodynamic coefficient is defined associated with the fairwater planes in differentially deflected mode

$$Z_{\delta_F} = \frac{(Z_{\delta_b} \cdot \text{moment arm})}{L}$$

$$Z_{\delta_F} = (0.00558 \times 7)/251.75$$

$$Z_{\delta_F} = 0.0015517.$$

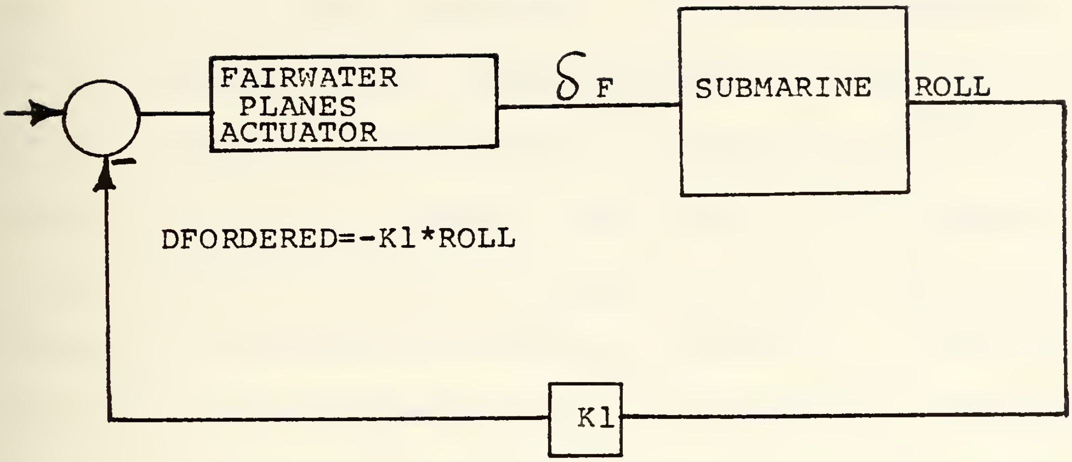
After the estimation of Z_{δ_F}, as a hydrodynamic coefficient, it is placed in the modified equation discussed above. After these modifications, in the equations of motion all of the term which is a function of the δ_b(sailplane deflection in the conventional mode) was set to zero by defining $\delta_b = 0$. As result, the equation of motion about the X-axis (roll axis) has correlative term between the fairwater plane and roll angle of the ship so that this additive moment term can be used to give feedback to smooth the snap roll.

B. ROLL CONTROLLER DESIGN

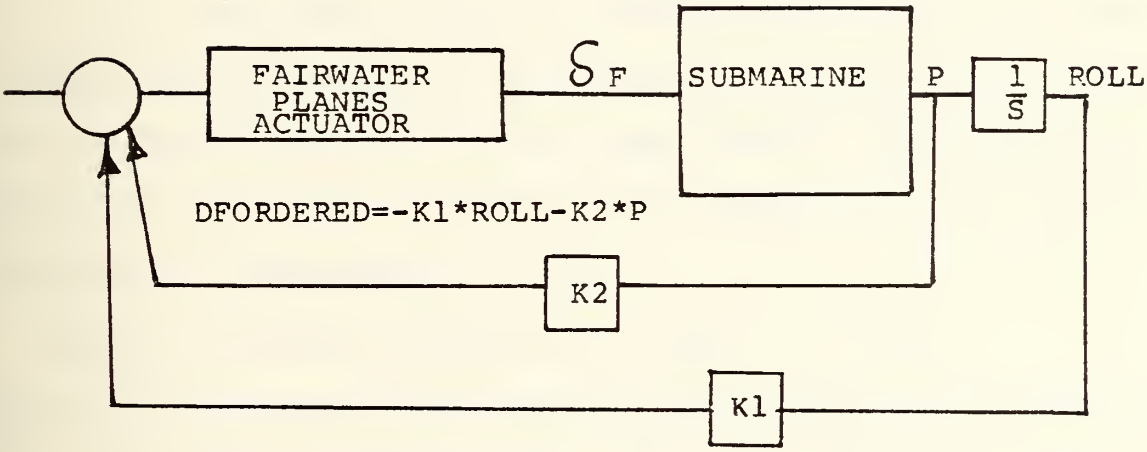
In contrast to the depth and pitch controller, the roll controller was designed by using the nonlinear equations of motion and linearizing was not attempted. In the previous section, the modification of the roll moment equation due to the imposition of moment term which stems from the fairwater

planes deflection was discussed. All through the roll controller design this modified version of the equations was used. The reason that led to using six nonlinear equations was such that linearizing of this equations in six dereee of freedom was found difficult because of the terms coupled with each other and mainly was thought that from the output of the system dynamics the roll angle and the roll rate (p) could give enough feedback information to accomplish the compensation.

The principles for designing the roll controller were simple. If the ship has a positive roll angle (starboard) the fairwater plane is to be deflected so that it can give negative roll moment, i.e., starboard sailplane is to be deflected leading edge up while port sailplane is deflected leading edge down or vice versa. As long as the ship has a roll angle this would cause the fairwater plane deflection by way of the feedback channel used. In the design it was assumed that, the fairwater planes actuater was capable of giving equal amounts of deflection command in opposite directions to both starboard and port sailplanes. Since the design was to invoke extensive simulation study (since nonlinear equations were used) in determination of the feedback parameters, the first basic controller attempt was the proportional controller because of its simplicity to design and implement. The proportional controller is shown in Figure 57.1. Referring to the figure, if the submarine has a roll angle this would give the position feedback to force the system to reach zero roll



-1-



-2-

Figure 57.1. Position Feedback Controller.
.2. Position And Velocity Feedback Controller.

angle position. Determination of K1 (proportional constant) was a trial and error process. Even though position feedback alone gave big improvement in the system dynamics, as is to be discussed in the following pages, it failed to stabilize the system in some operating conditions that are considered very likely to be faced. This leads to the compensation of the system by velocity feedback and other modifications (Limiter in the position feedback channel). In the following pages the design procedure which uses extensive computer simulation is discussed from the simplest case of proportional controller to the last modification that stabilized the system in various operating conditions and over a wide range of speeds.

1. Proportional Controller

The first attempt to control the roll was to design a proportional controller as is shown in Figure 57.1. Referring to the figure, it is seen that ordered fairwater plane deflection is a function of the roll angle and the proportional constant K1. Such that

ORDERED FAIRWATER DEFLECTION = DFOD = -K1*ROLL

Since the reference signal is zero the system always looks for zero roll angle. Ordered fairwater deflection as an input to the fairwater planes actuator causes deflected planes at the output due to the actuator dynamics. Actuator dynamics were the same as those of the sternplanes actuator shown in Figure 39. With the counter roll moment created differentially deflected fairwater planes, system dynamics try to decrease the roll angle.

Determination of K1 was a trial and error process. The stability range was 1 through 4. By inspection of the results of computer simulations, K1 = 3 was chosen as a best choice in the sense of snap roll and steady state value of the roll responses. With the determined K1 = 3 value the system was tested at 24 knots approach speed to a 35° rudder command and the results are shown in Figures 58 through 62. Before analyzing the results it is instructive to indicate here that all through the design procedure the worst condition that could happen was always taken into account. For this reason the controller was designed at 24 knots base speed and to a 35° constant rudder angle which could give the worst snap roll in the range of speed of interest. By looking at the Figures 58 through 62, the following results can be summarized:

1. As was predicted, the snap roll decreased to almost $4^{\circ}.6$ from 37° and roll response reached a steady state value of $3^{\circ}.5$. In Figures 52, 53, and 54 it was shown that before implementation of the roll controller the system was unstable to an identical test. Adding the roll controller made the system stable at high speed. In depth and pitch responses great improvement has been made. Steady state values of the depth and pitch were almost 8 feet and $4^{\circ}.5$ which were acceptable. While this depth, pitch and roll control improvement has been obtained, the stern and sailplane was used moderately such that they didn't reach any saturation ($\pm$ 35°).

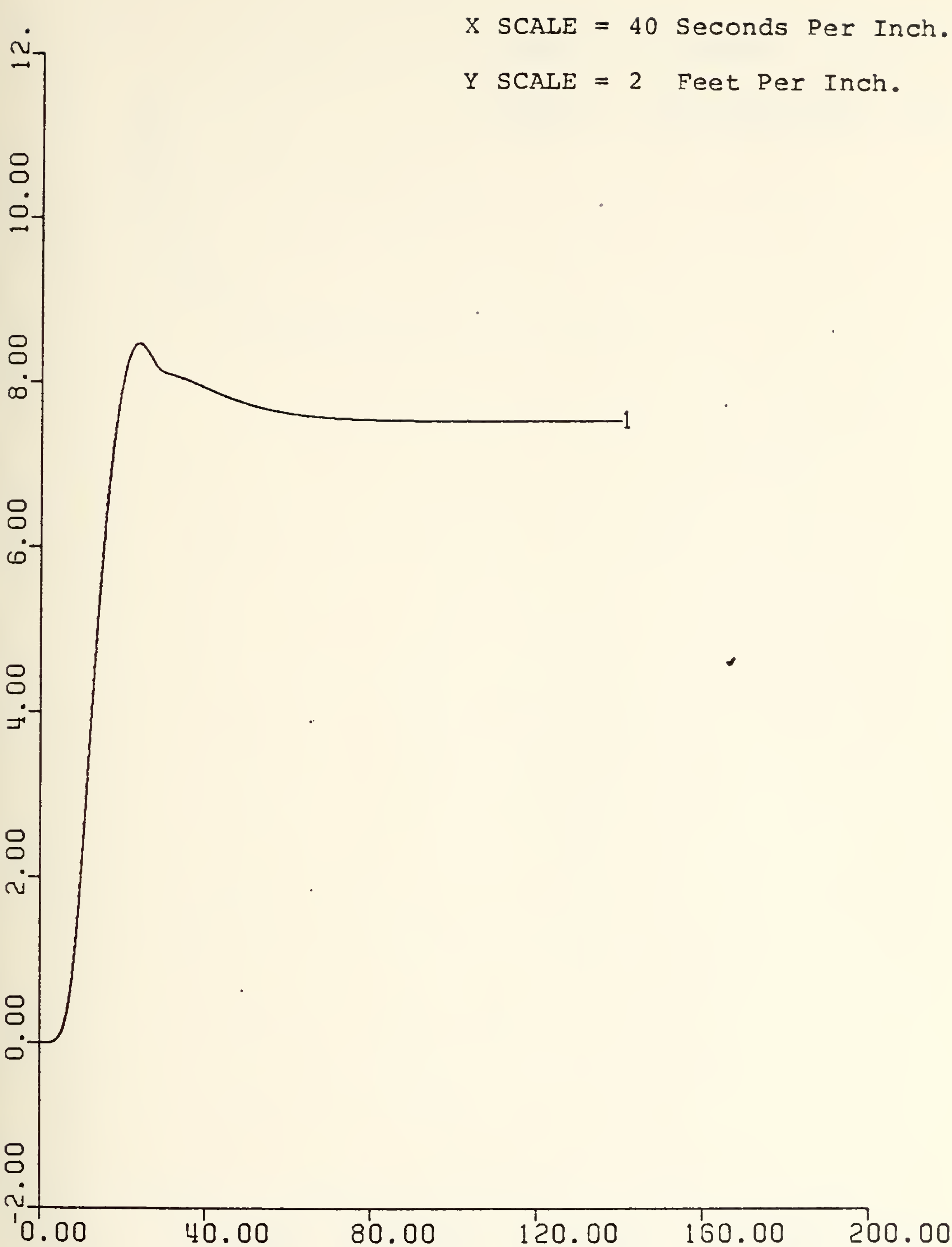


Figure 58. Depth vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

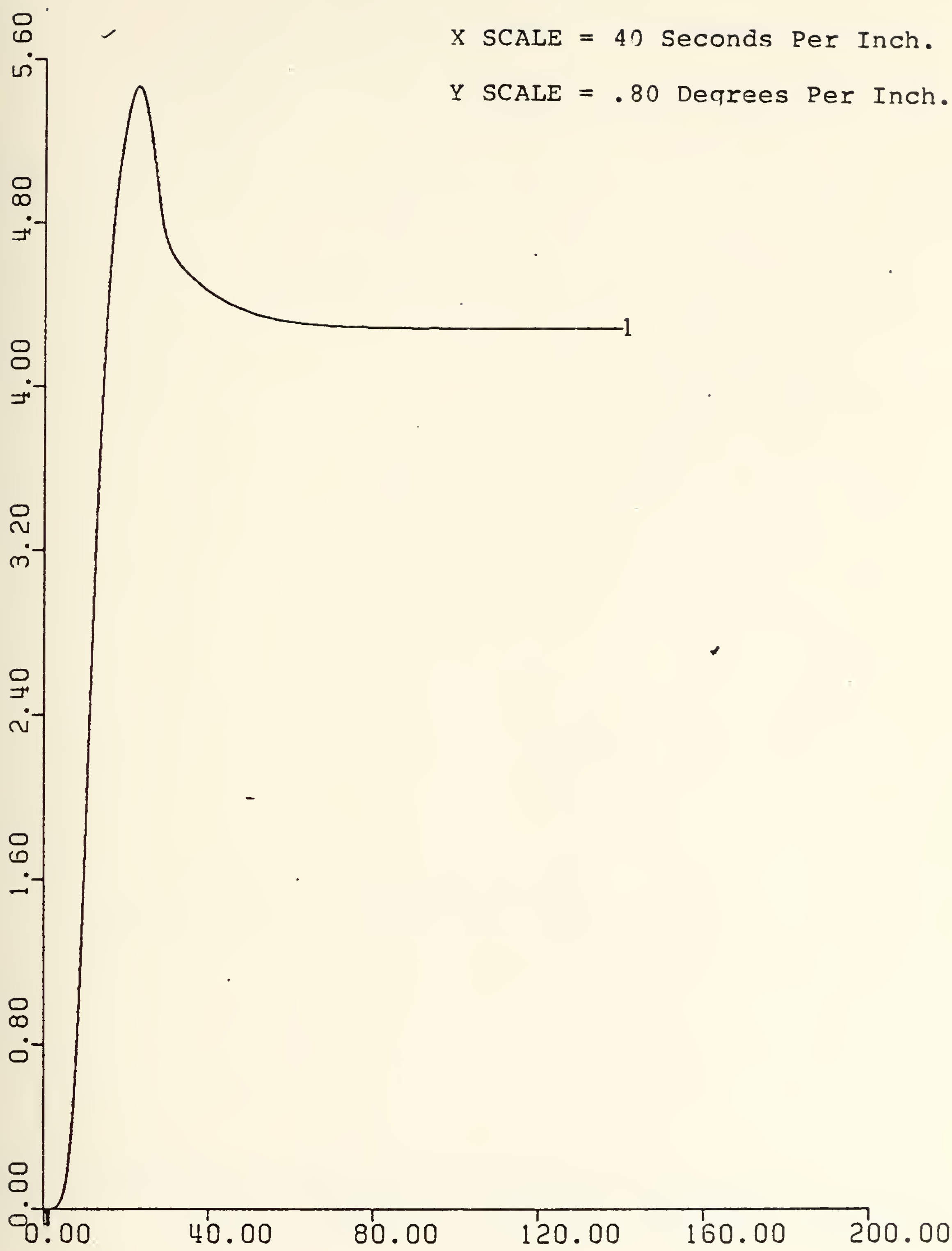


Figure 59. Pitch vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

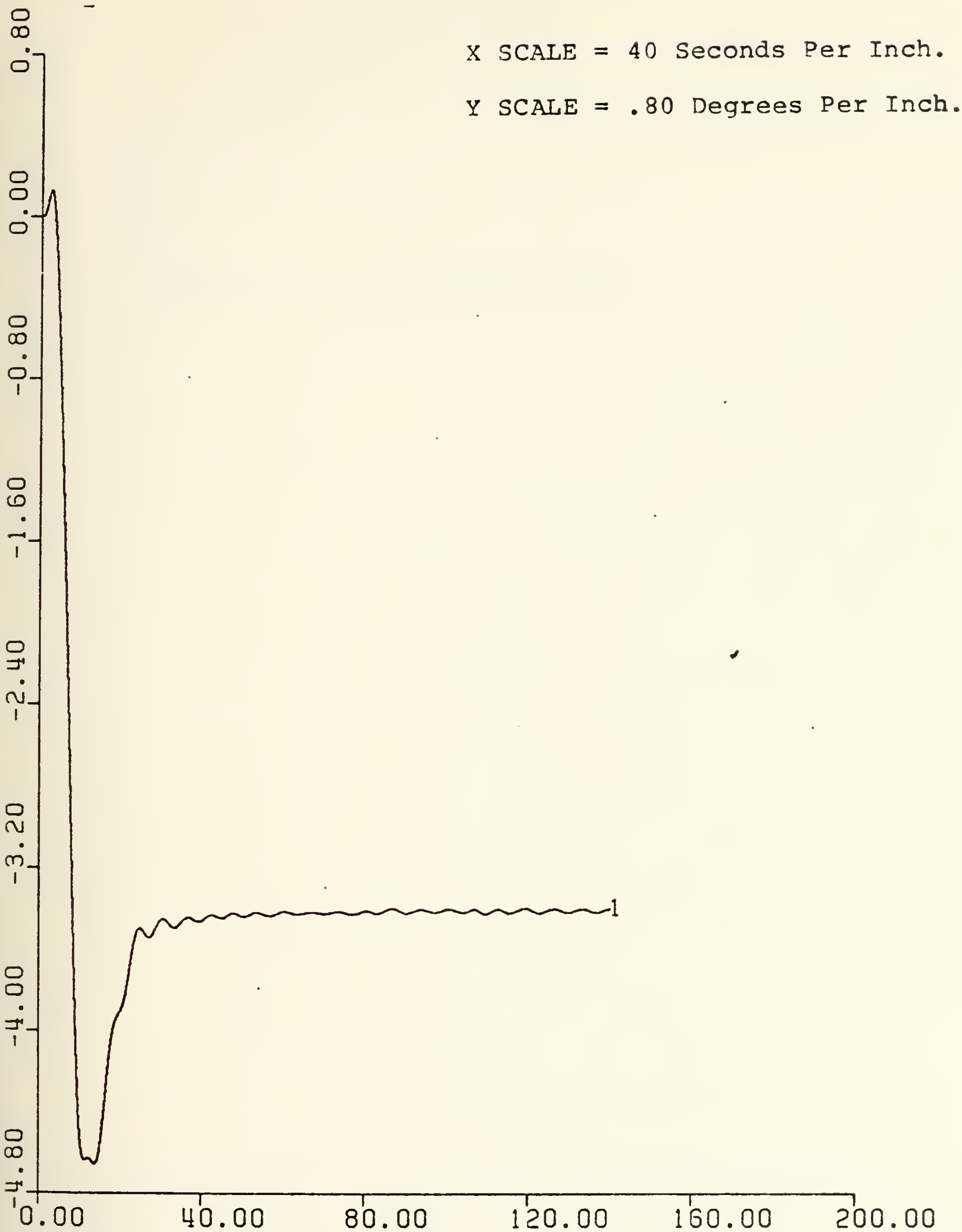


Figure 60. Roll vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

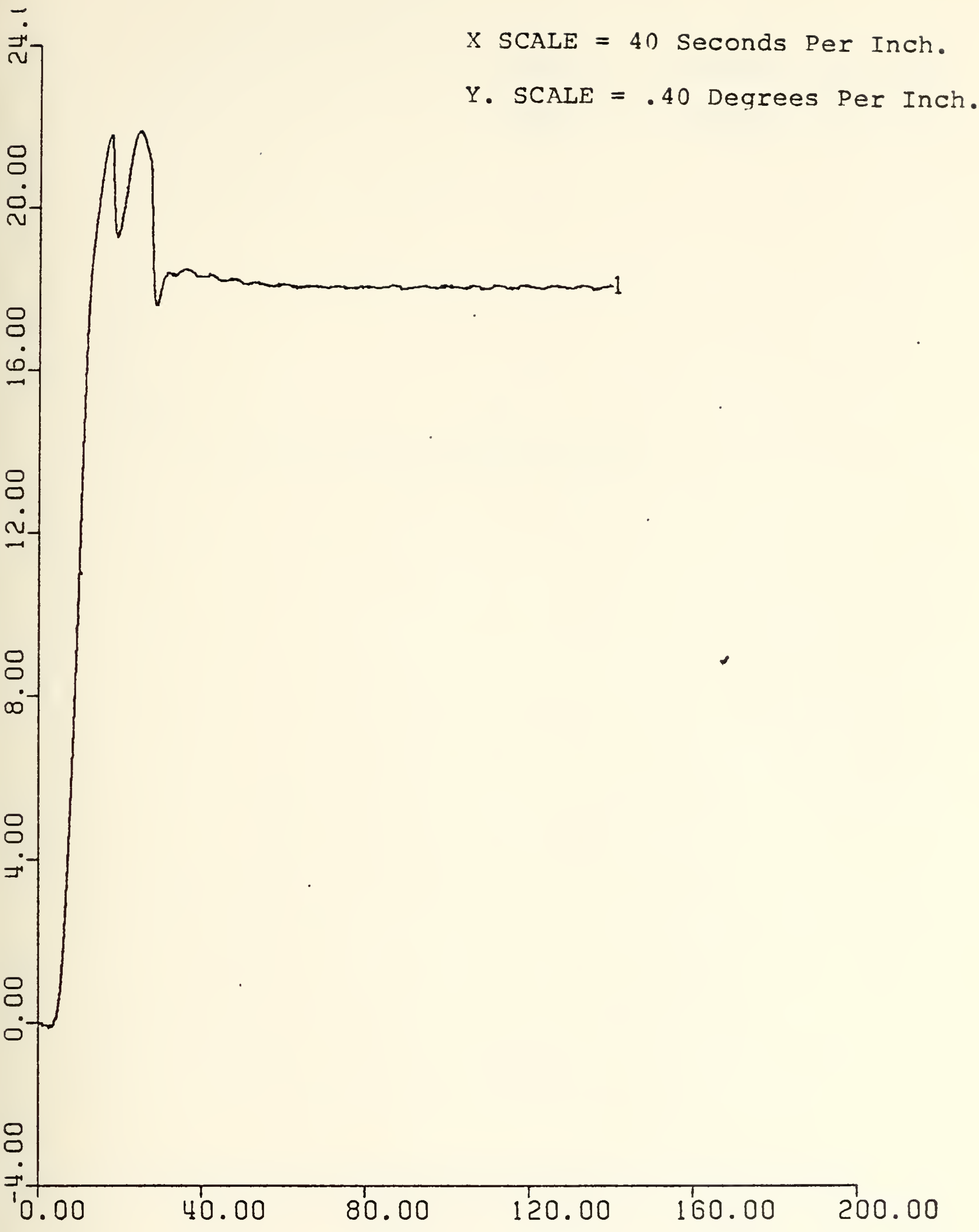


Figure 61. Sternplane Angle vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

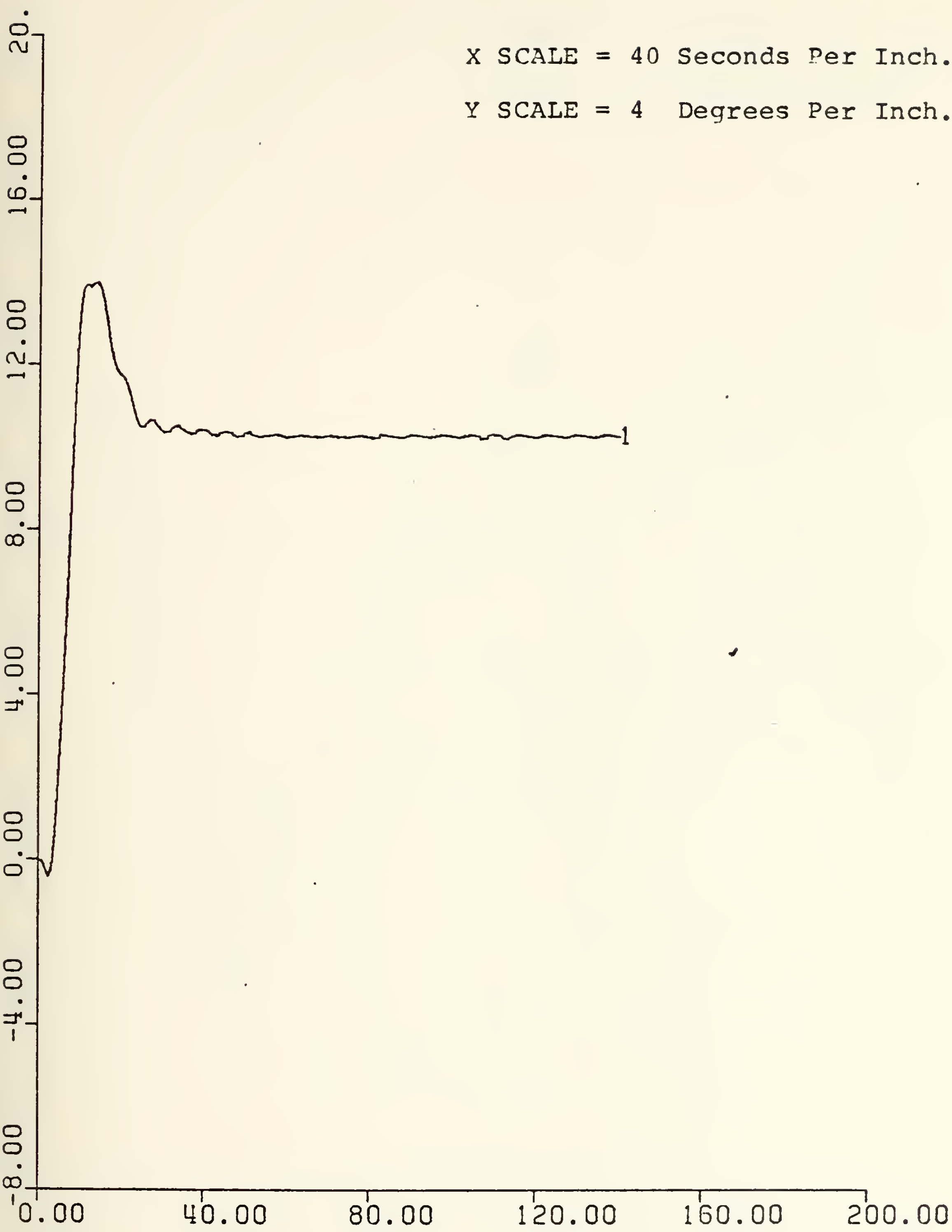


Figure 62. Sailplane Angle vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

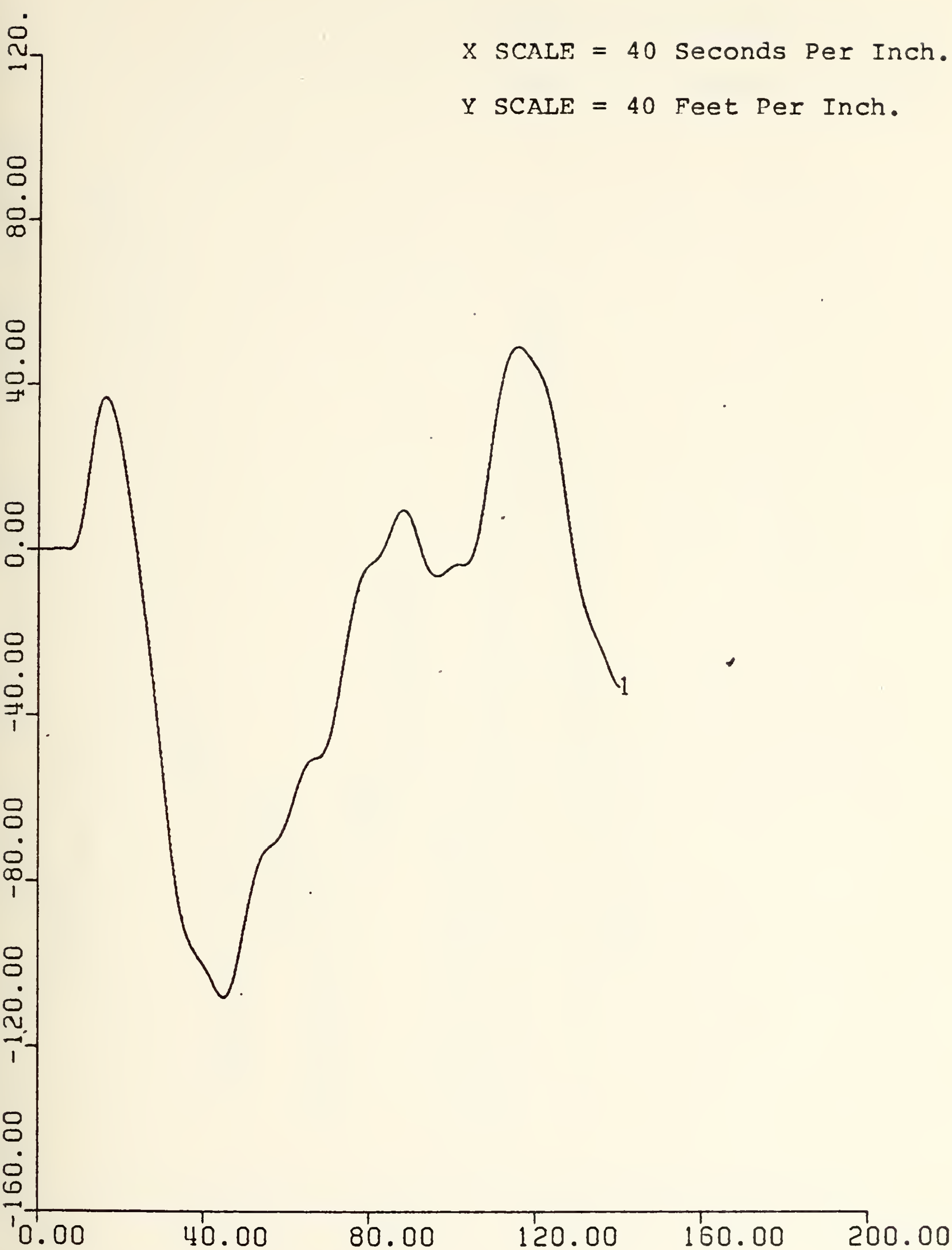


Figure 63. Depth vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = -5°.

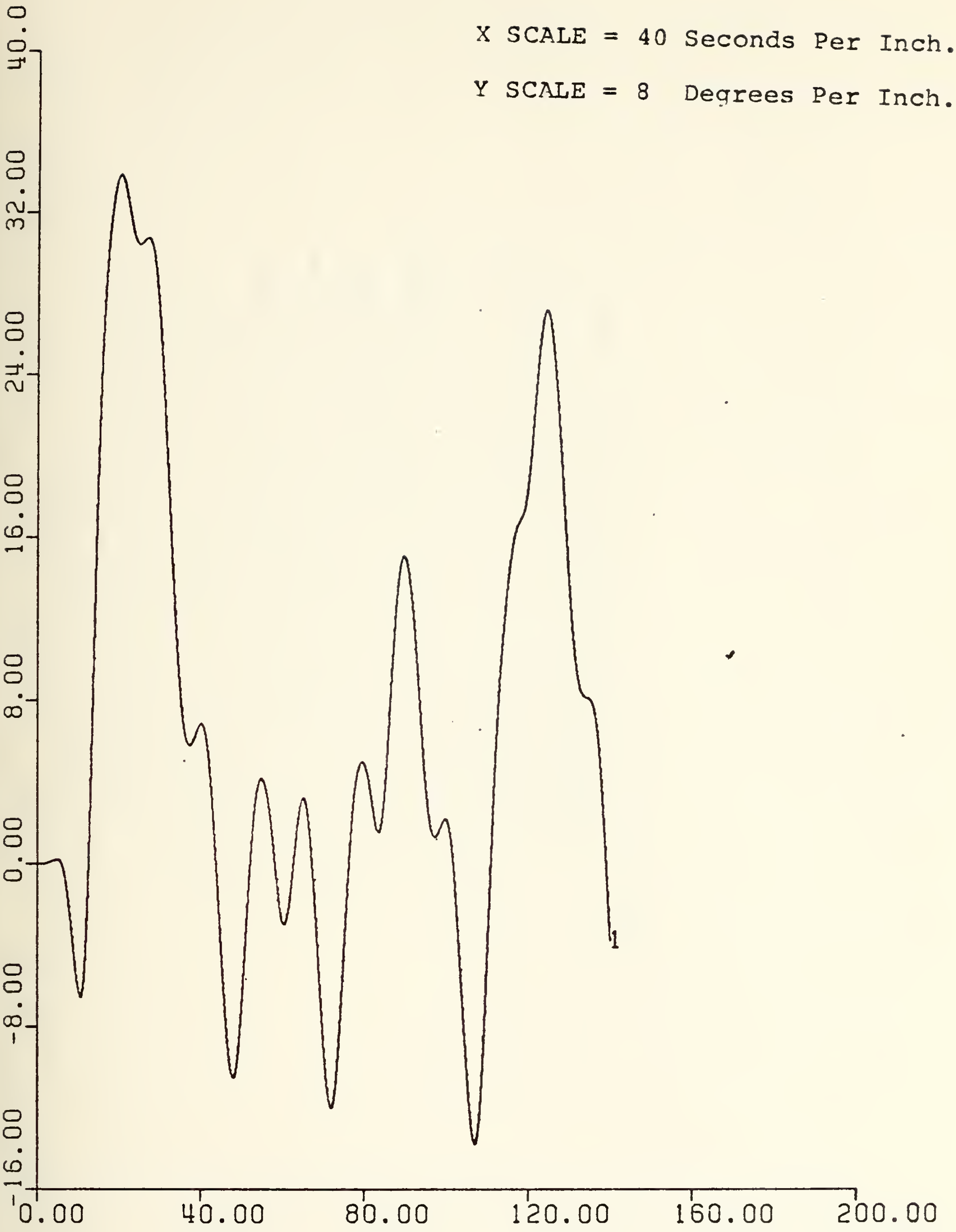


Figure 64. Pitch vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = -5°.

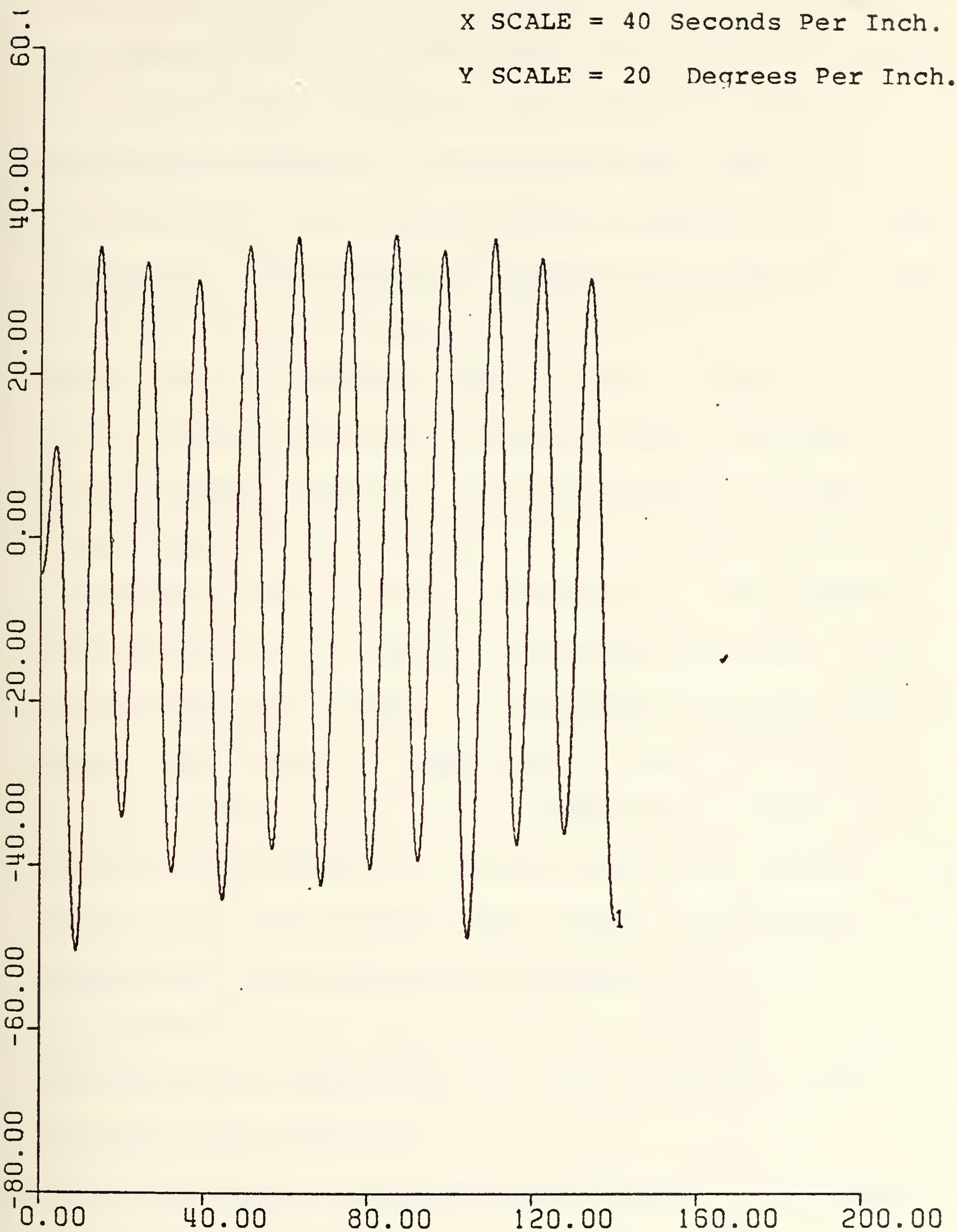


Figure 65. Roll vs. Time. K1 = 3. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = -5°.

2. Investigation of the roll response in Figure 60 lead to further study. In the steady state value of the roll, the oscillation with almost fixed amplitude and frequency was observed. The amplitude was around 0.1^{o}. As a first guess, the oscillation was thought to be a stable limitcycle. To expose the problem the system was tested with initial roll response (5^{0} inboard roll angle) at 24 knots to a 35^{o} constant rudder angle. Figures 63, 64, and 65 record the depth, pitch, and roll responses. The system became unstable. The system failed to compensate itself when it was commanded to turn with the 35^{o} rudder deflection and 5^{o} initial inboard roll. Any submarine maneuvering in the tactical area may experience a turn with initial roll angle. Disturbances from the heavy sea state might cause the submarine to roll eventhough it is in a straight course. If the submarine is commanded to turn at this moment, it was shown that its control is lost. That is why the situation was thought unacceptable and compensation of the system was attempted. It was thought that the reason for the failure was lack of enough feedback information and compensation of the system with velocity feedback was attempted.

The following section describes the modification and improvement obtained.

2. <u>Compensation Of The System With Velocity Feedback</u>

The modified controller block diagram is shown in Figure 57.2., and DFOD = -K1*ROLL-K2*P.

It was felt that the velocity feedback should give to the system better damping and better stability characteristics. Determination of the K2 value was again a trial and error process and the stability range was found to be 1 to 15 by computer simulation. By inspection of the results of the tests with different K2 values, K2 = 10 was considered the best choice in the sense of snap roll (max roll) and steady state value of the roll responses. Since the reason for introducing velocity feedback was instability in the presence of an initial roll angle, tests with exaggerated initial roll (20° inboard) were made. It was previously denoted that the ship has almost 37° snap roll at 24 knots to a 35° rudder command. To force the ship to turn with a hard rudder command when it already has a very serious initial roll angle was thought a good example of the capability to control the ship in three dimensions. In fact, any submarine cruising in a straight course is unlikely to face this much roll angle from heavy seastate. In Figure 66 the result of this test is shown. Before the implementation of the velocity feedback the system was unstable to a turn command with initial 5° roll angle. And now it is stable even with 20^{0} initial inboard roll. The result was such that steady state roll angle was almost $4^{\circ}.5$ and before reaching steady value on oscillation with decreasing amplitude was observed. In all of the aforementioned tests, the ship response was investigated to a steady 35° rudder command. The rudder was commanded to a 35° deflection at the beginning of the simulation and after reaching 35° it was not

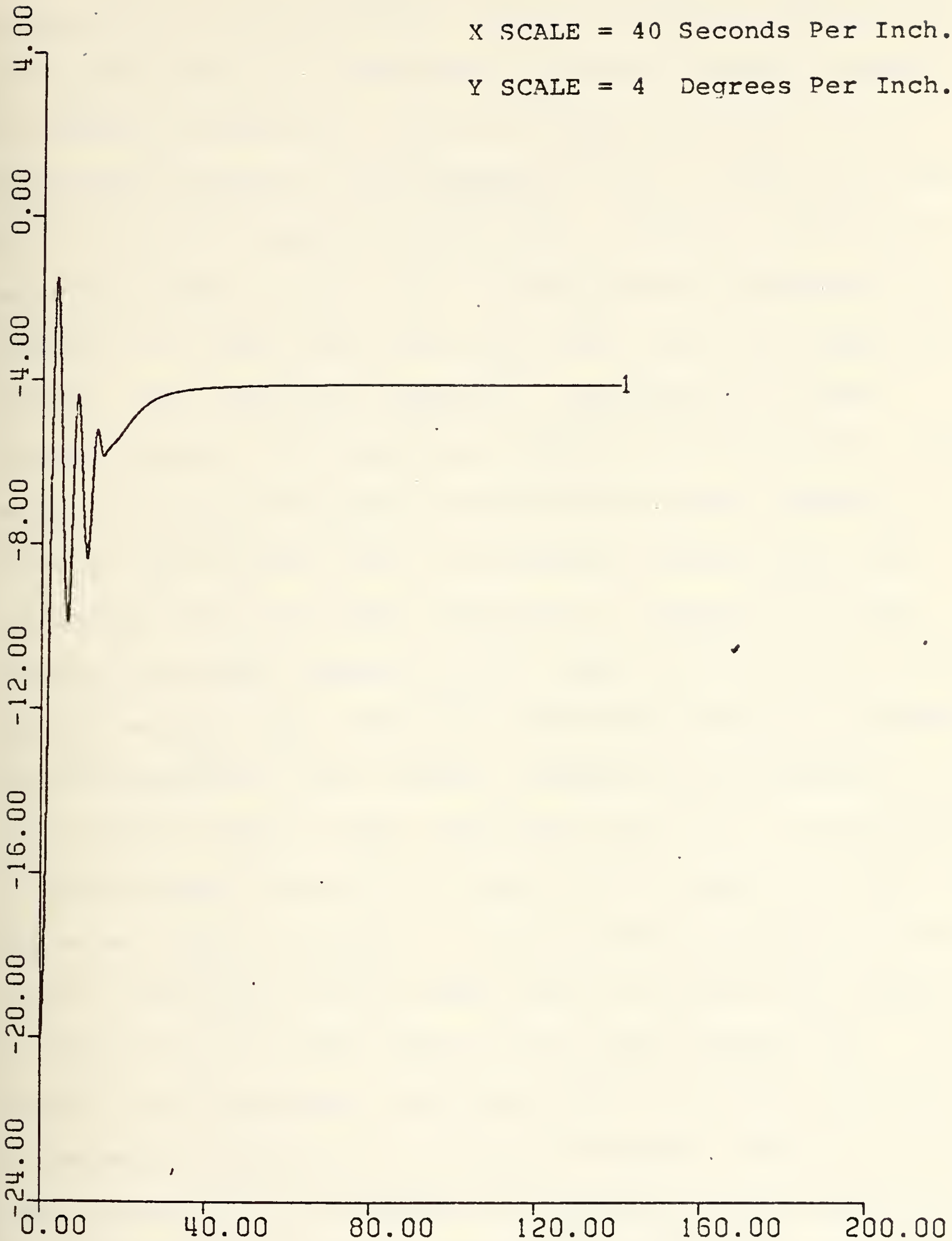


Figure 66. Roll vs. Time. K1 = 3, K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = -20°.

changed to any other command. But any submarine maneuvering in tactical areas can experience successive rudder commands in opposite directions. For this reason the test, in which the rudder deflection was commanded to 35° in the time interval of 20 to 80 seconds was required. Figures 67 through 71 record the depth, pitch, roll, sternplane and sailplane deflection. In this test the initial roll angle was again 20° inboard. The result was unstable. Inspection of these figures reveals a very important reason of the failure. Curve number 2 in these figures represents the rudder response. But since in the vertical axis the automatic scaling was used associated with the output responses of interest, in some figures the rudder response in the time interval of 20 to 80 seconds was seen less than 35°. For this reason, to overcome misinterpretation, curve number 2 should be interpreted as the time interval where rudder deflection was 35°. By inspection of the figures 67 and 68 its seen that the depth and pitch response are almost unchaged. The very small changes are due to the roll oscilation which stems from the initial roll angle. In Figure 70 it is shown that in the time interval of 0 - 20 seconds the sternplanes oscillate with very small amplitudes to compensate these depth and pitch changes. But in the same time interval (0 - 20 seconds) the sailplanes oscillate with big amplitudes to overcome the roll oscillation started with the initial 20° inboard roll angle (Figure 71). Because of the roll controller, the initial roll angle has more effect

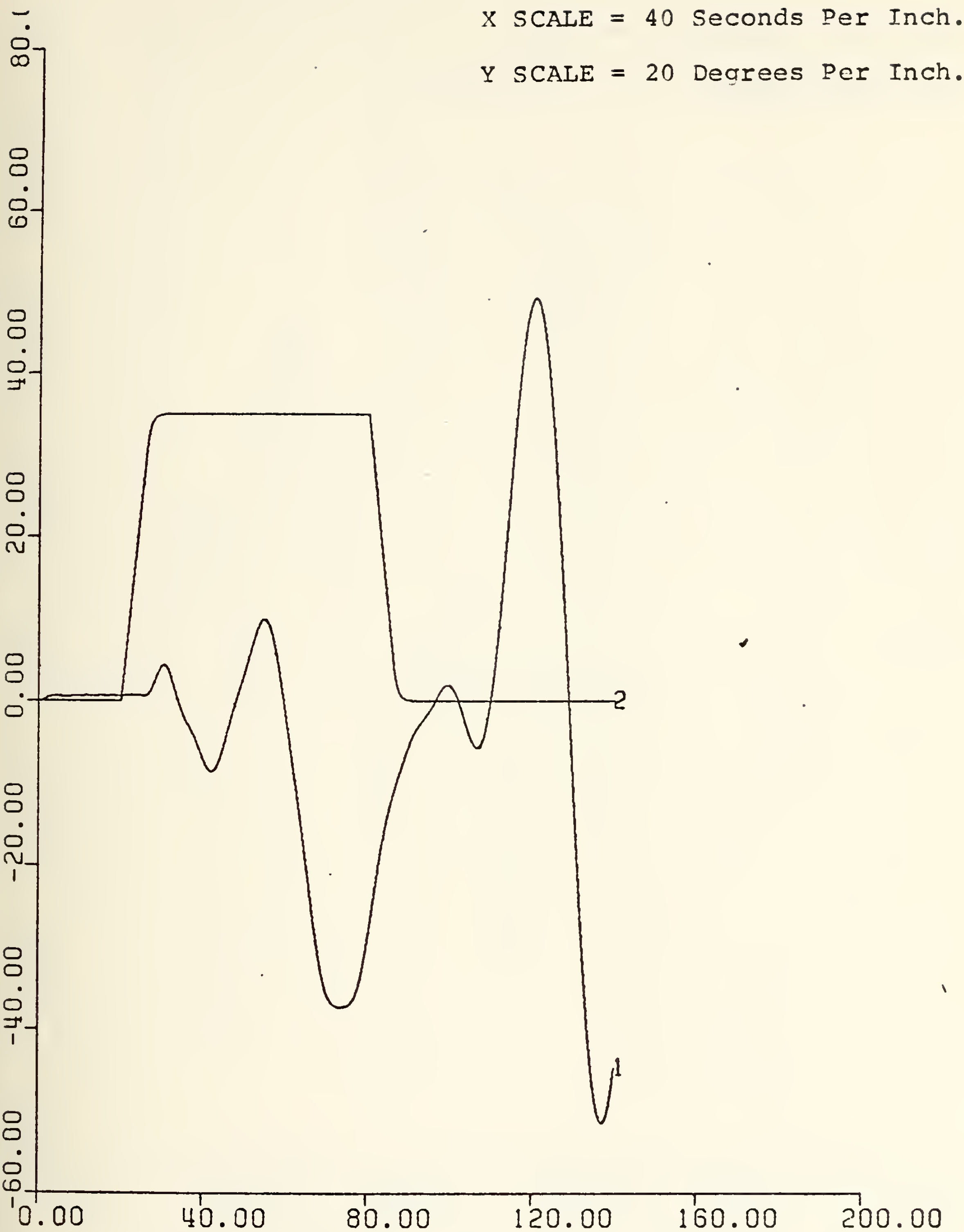


Figure 67.1. Roll vs. Time. K1 = 3, K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time. (Rudder Ordered = 35°).

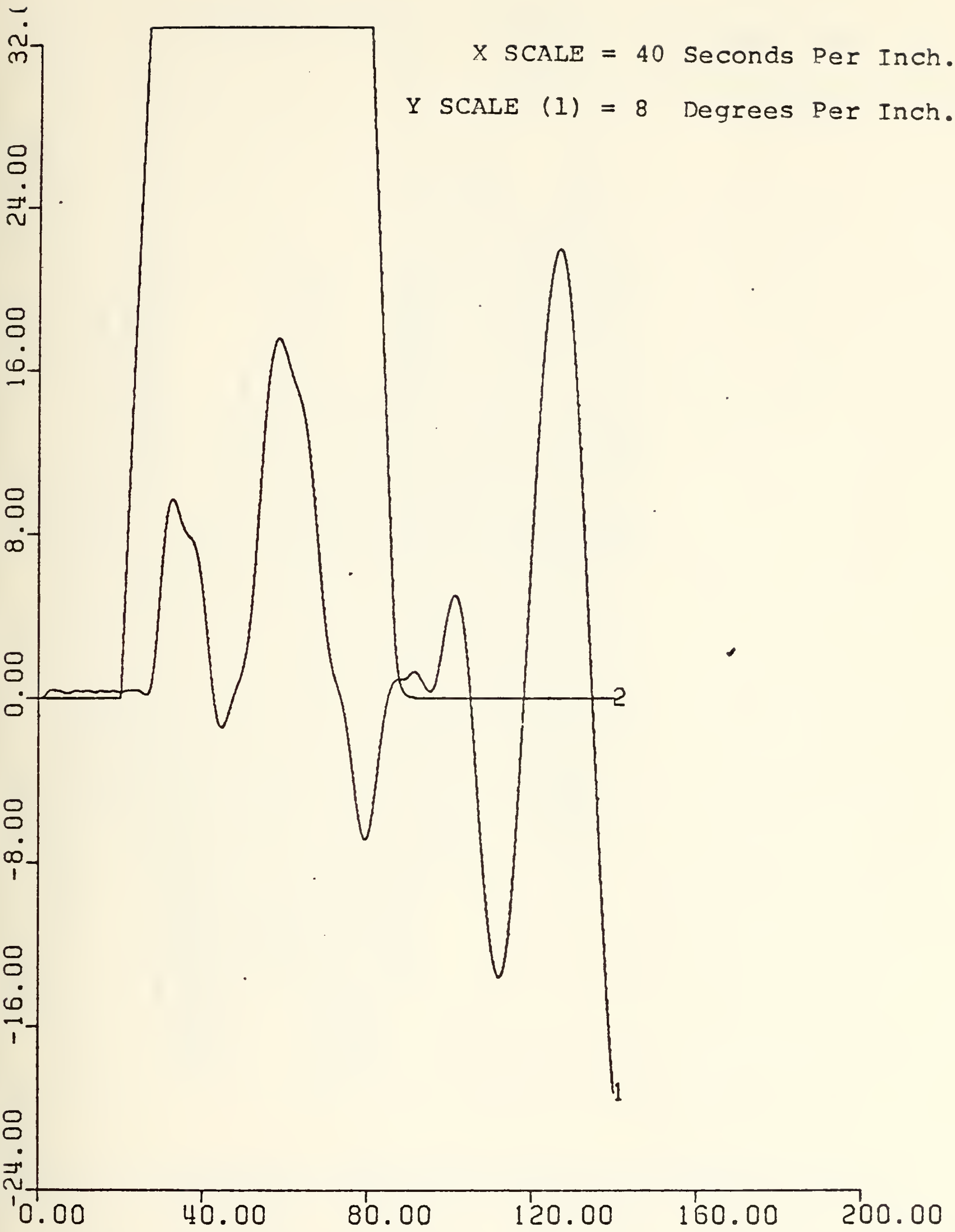


Figure 68.1. Pitch vs. Time. K1 = 3, K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time. (Rudder Ordered = 35°).

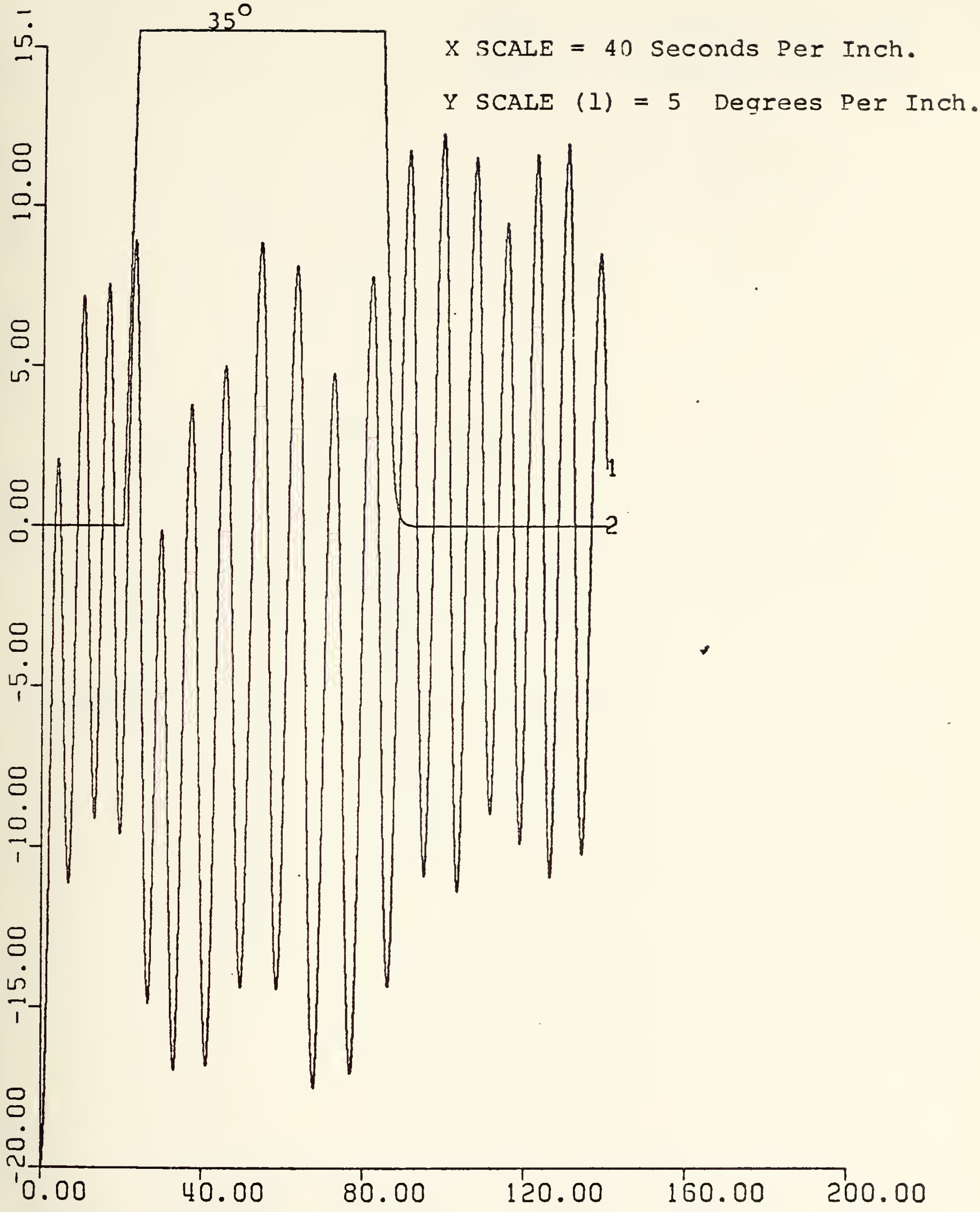


Figure 69.1. Roll vs. Time. K1 = 3, K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°.)

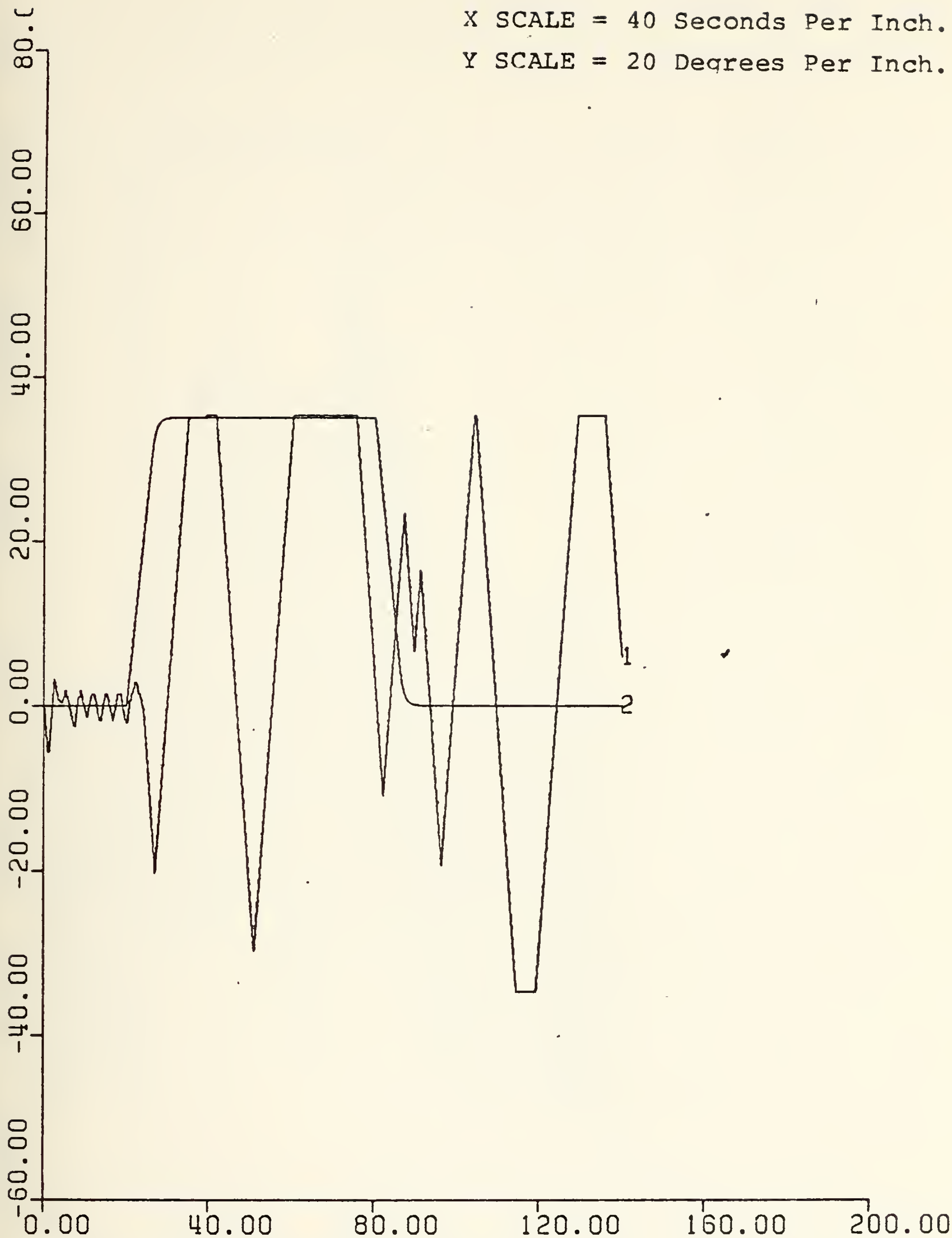


Figure 70.1. Sternplane Angle vs. Time. K1 = 3, K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20°.
.2. Rudder Response vs. Time (Rudder Ordered = 35°).

X SCALE = 40 Seconds Per Inch.
Y SCALE = 8 Degrees Per Inch.

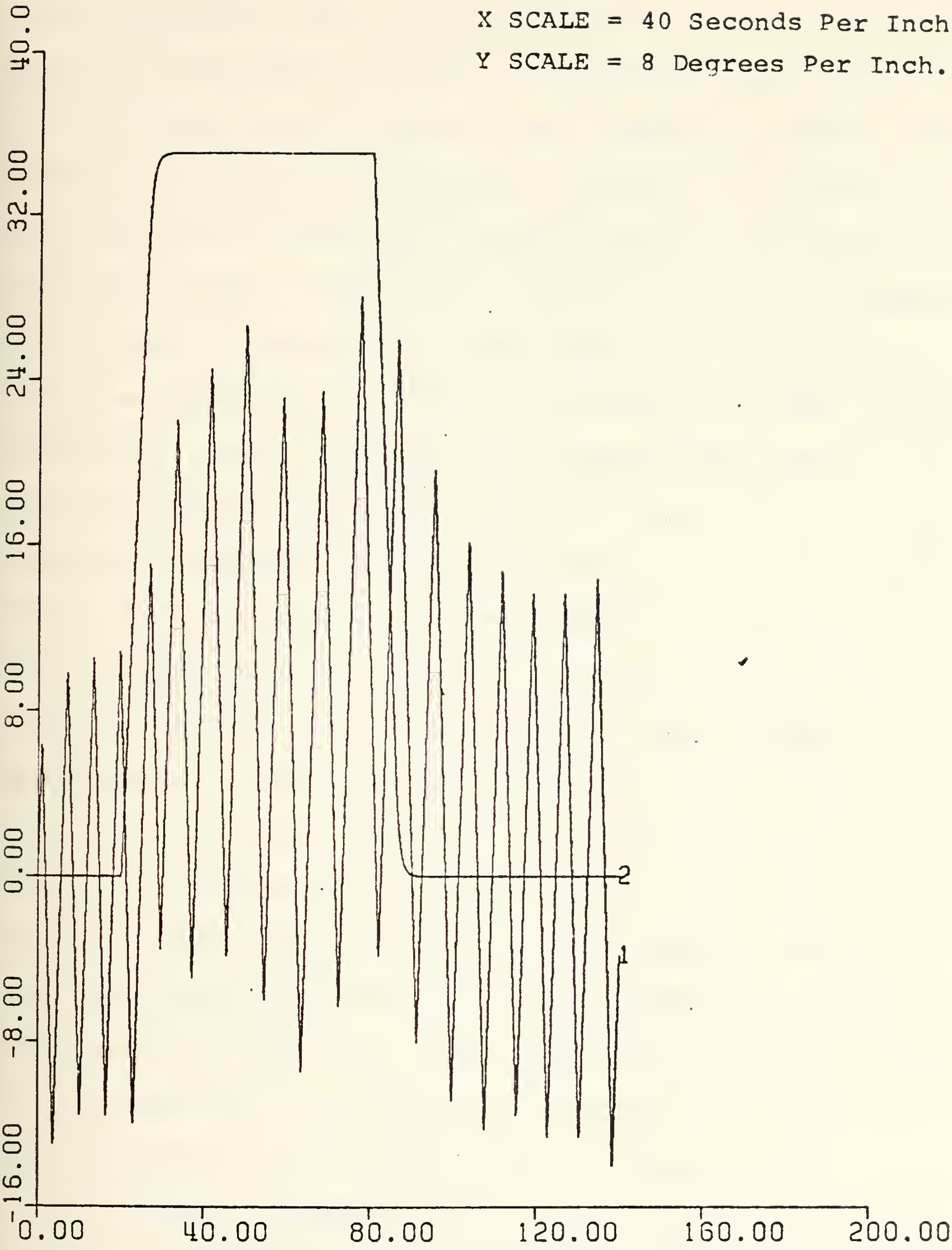


Figure 71.1. Sailplane Angle vs. Time. K1 = 3, K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

on the sailplanes than on the sternplanes. In the time interval of 0 - 20 seconds of Figure 69 the roll oscillation started with the initial roll angle is seen. Since the direct effect of the roll angle on the sailplane deflection, this initial roll oscillation causes the sailplane to oscillate and this oscillation causes initial roll oscillation not to be damped out. As this is going on, at time equal to 20 seconds the rudder was commanded to 35° full deflection and this gives more unstability. After analyzing this and previous results the following conclusion has been reached. Since the roll angle was directly fedback via K1, the sudden and big roll response changes cause the sailplane to oscillate with big amplitudes and this leads to unstability. To overcome this difficulty a limiter was placed in the roll error feedback channel with the magnitude of ±5 (The same reason had lead to the placing depth and pitch error limiter in the depth and pitch controller design as was discussed in Section IV.B.). After this last modification the system was tested under various conditions which are to be discussed below. The complete controller block diagram with the depth and pitch controller is shown in Figure 72. By inspection, the simulation results of the last version of the controller can be sumarized as follows:

1. In Figures 73 through 87 the depth, pitch, roll, sternplane and sailplanes responses at 24, 18, and 12 knots to 35° rudder command in the time interval of 20 - 80 seconds) with the initial 20° inboard roll angle are shown. The

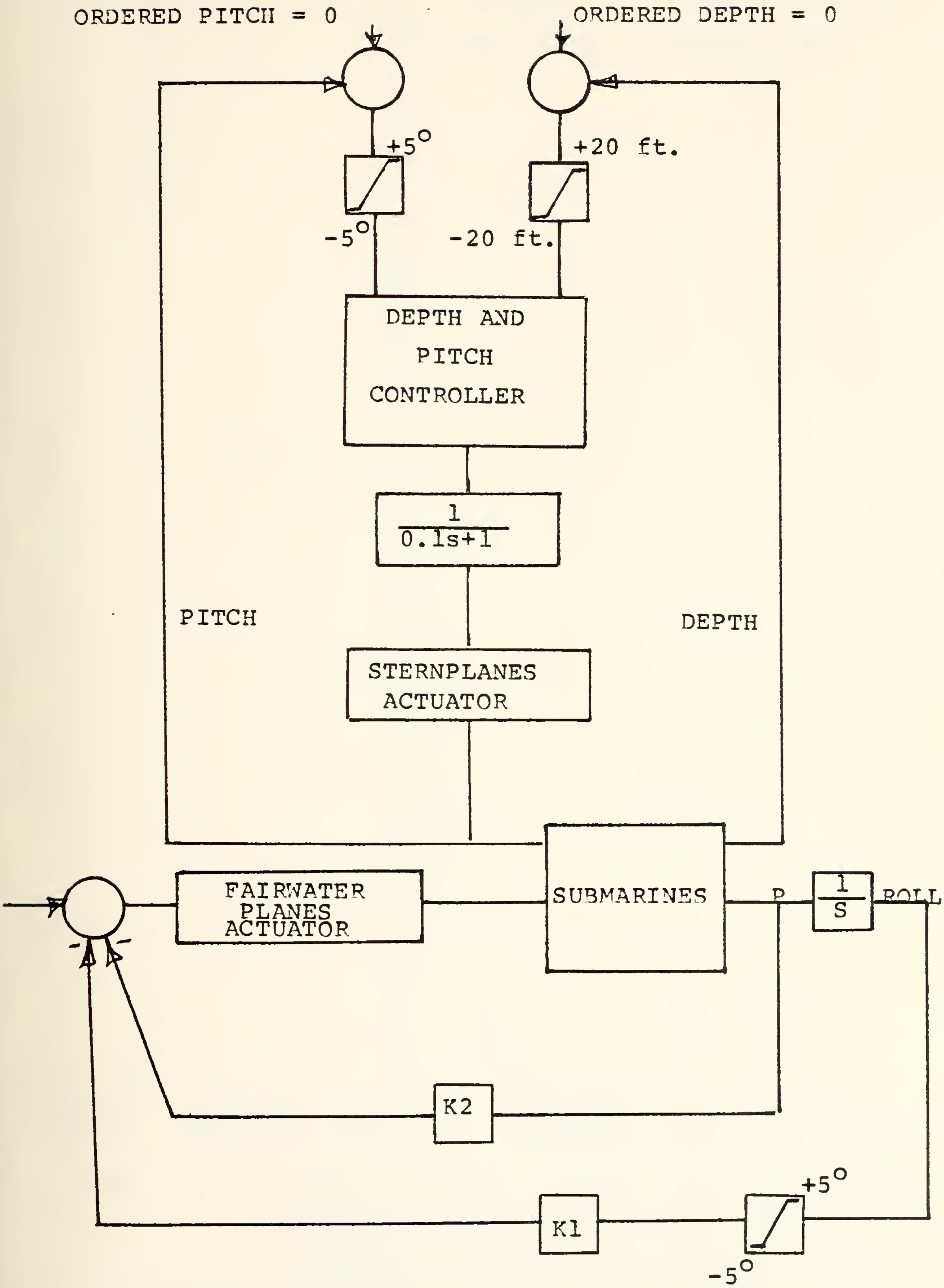


Figure 72. Complete Depth-Pitch-Roll Controller (Final Scheme)

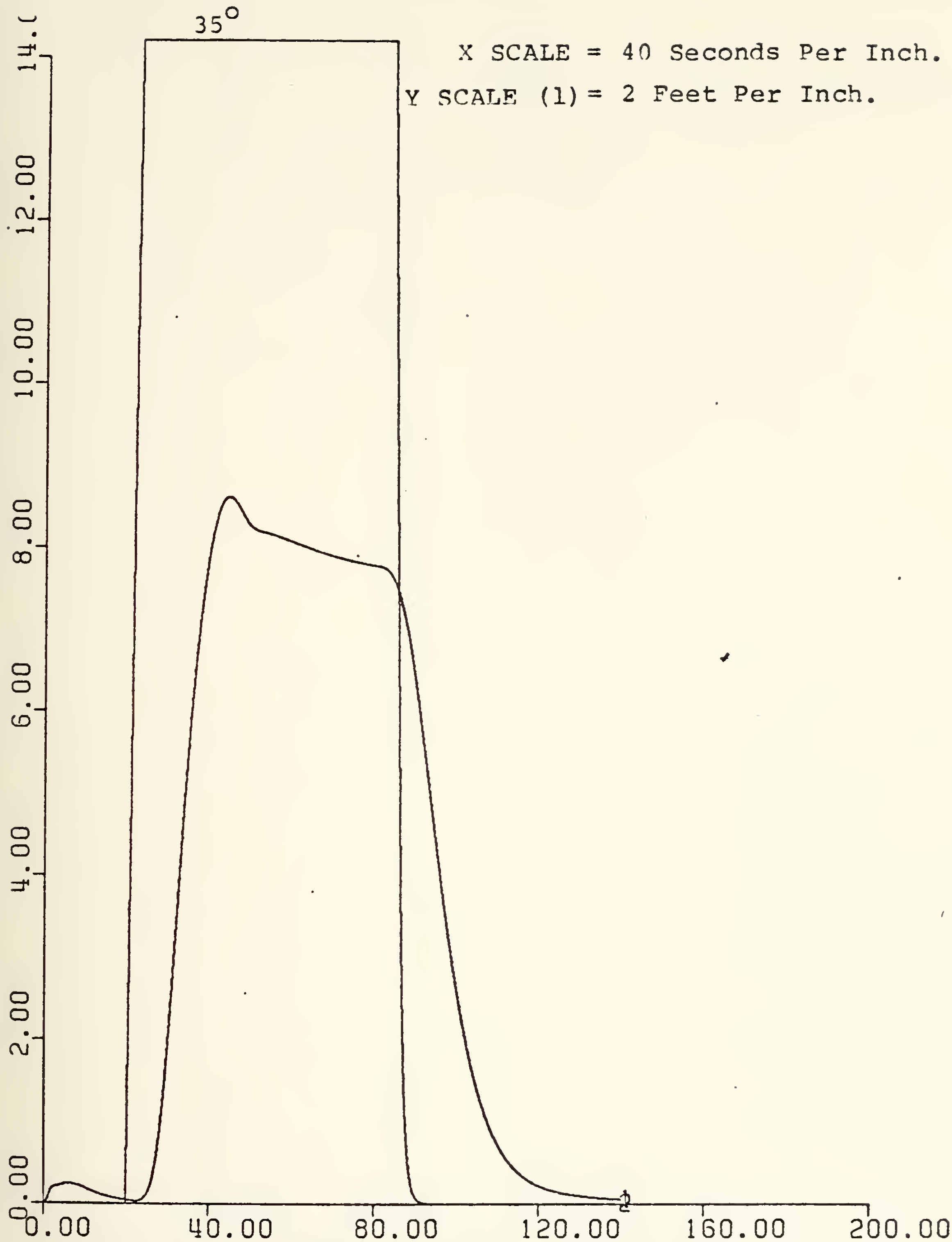


Figure 73.1. Depth vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time. (Rudder Ordered = 35°).

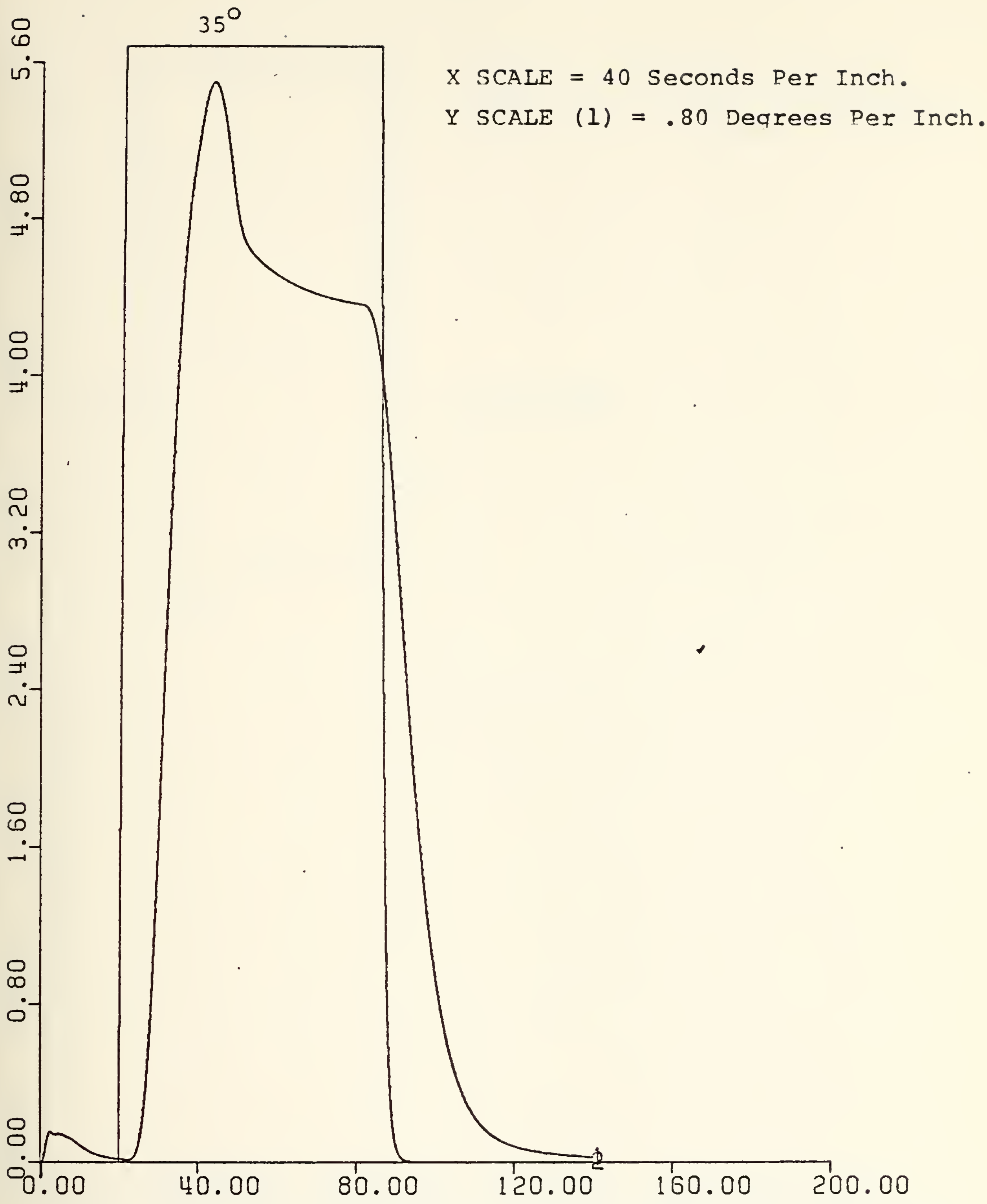


Figure 74.1. Pitch vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

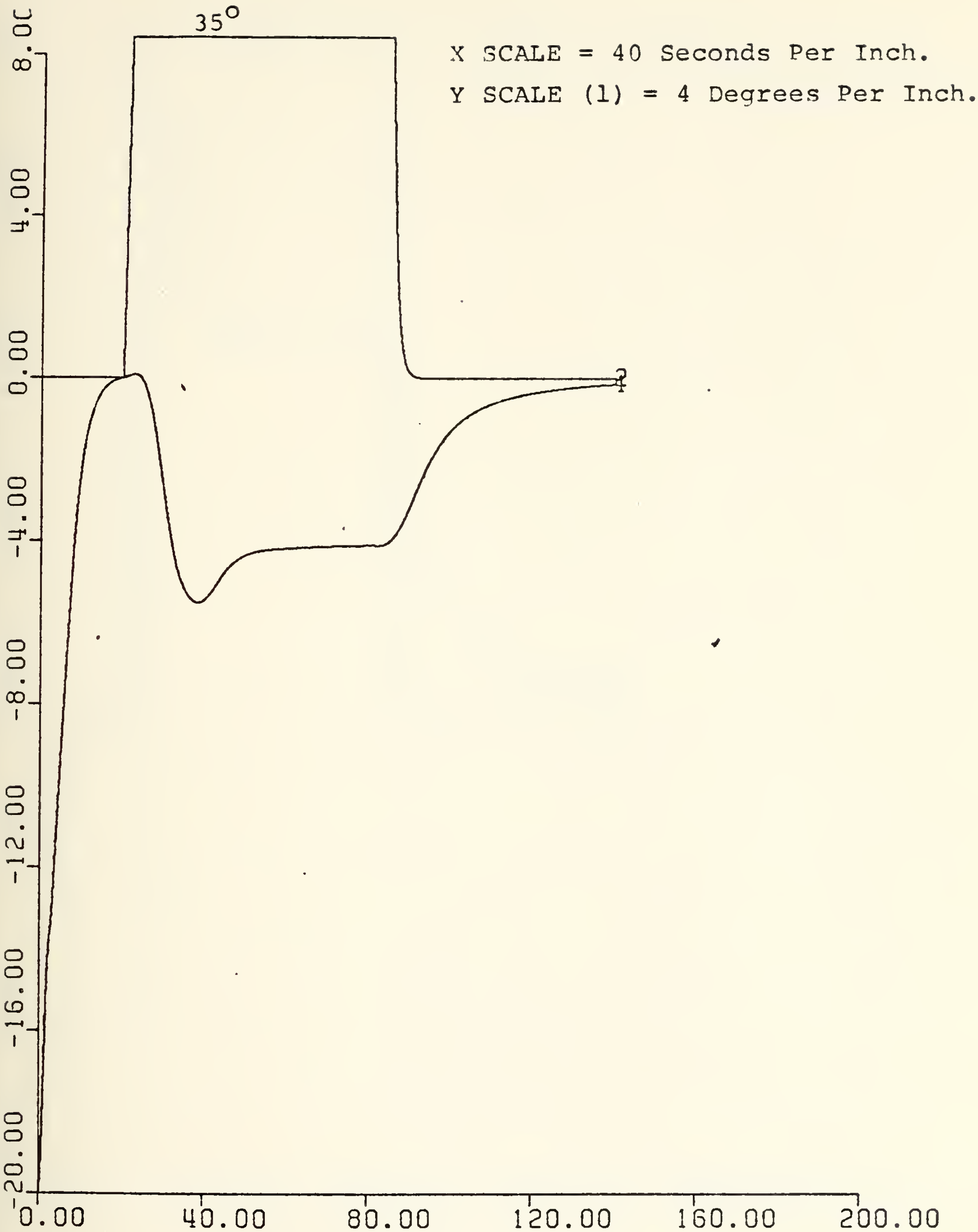


Figure 75.1. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time. (Rudder Ordered = 35°)

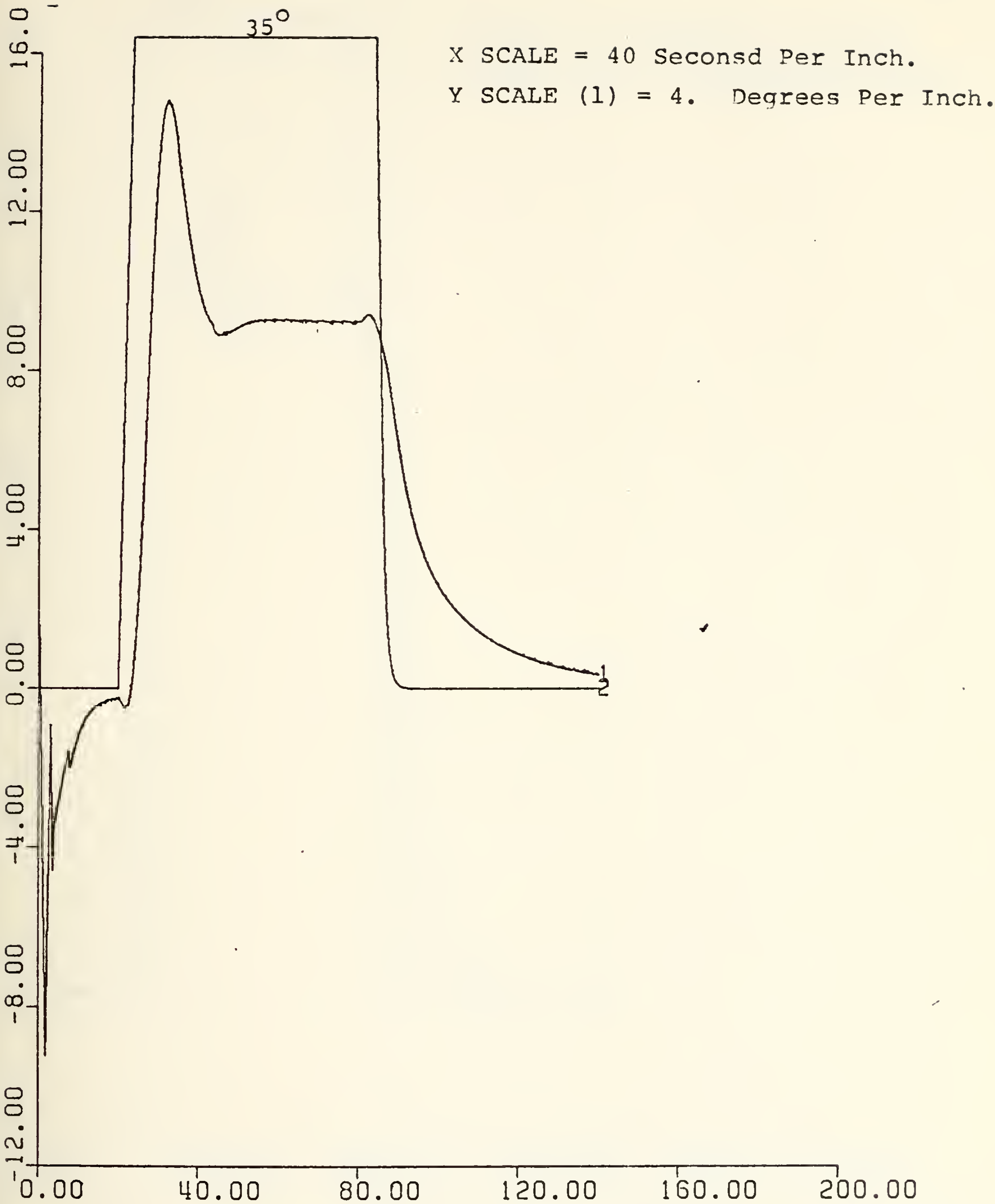


Figure 76.1. Sternplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

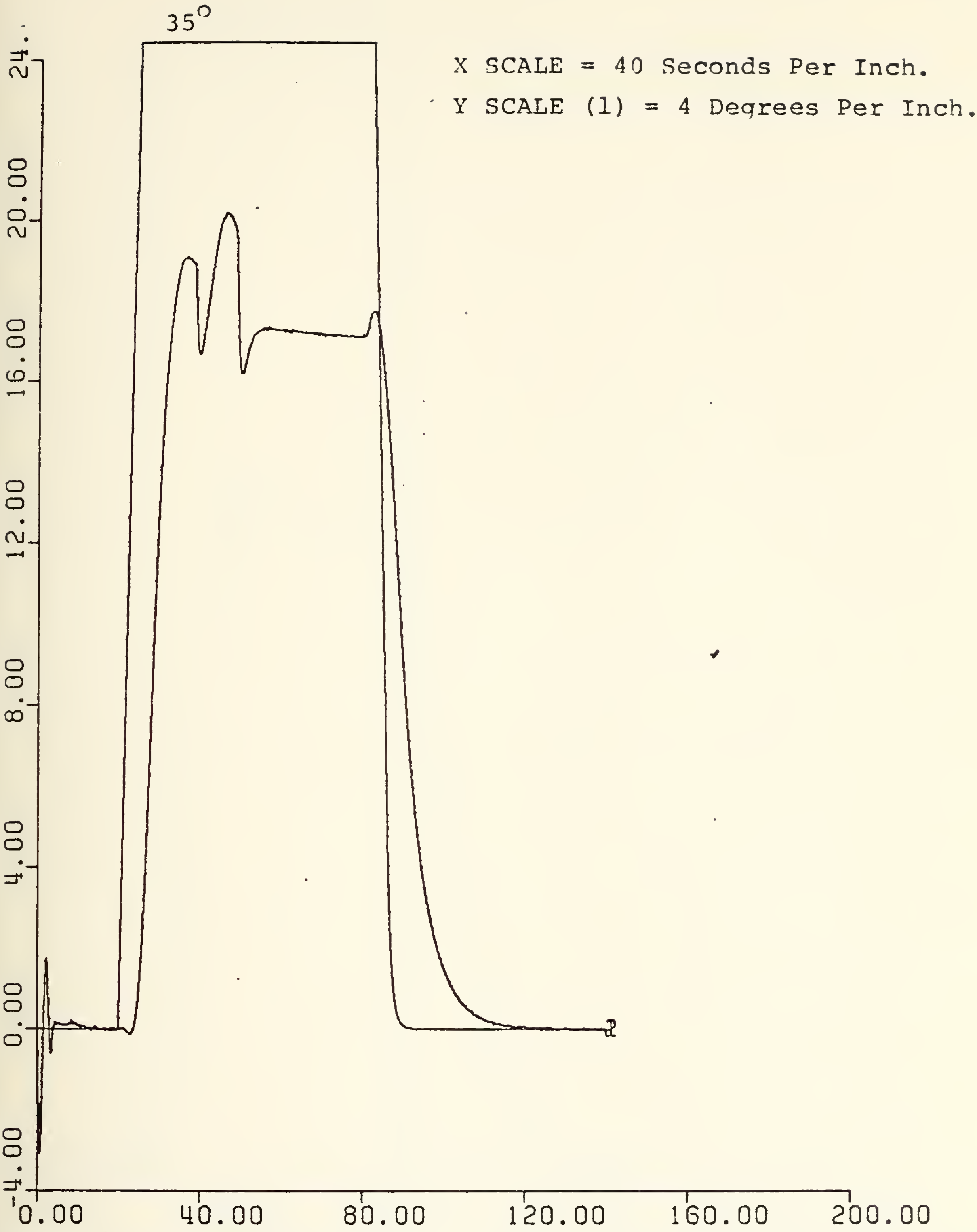


Figure 77.1. Sailplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 24 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

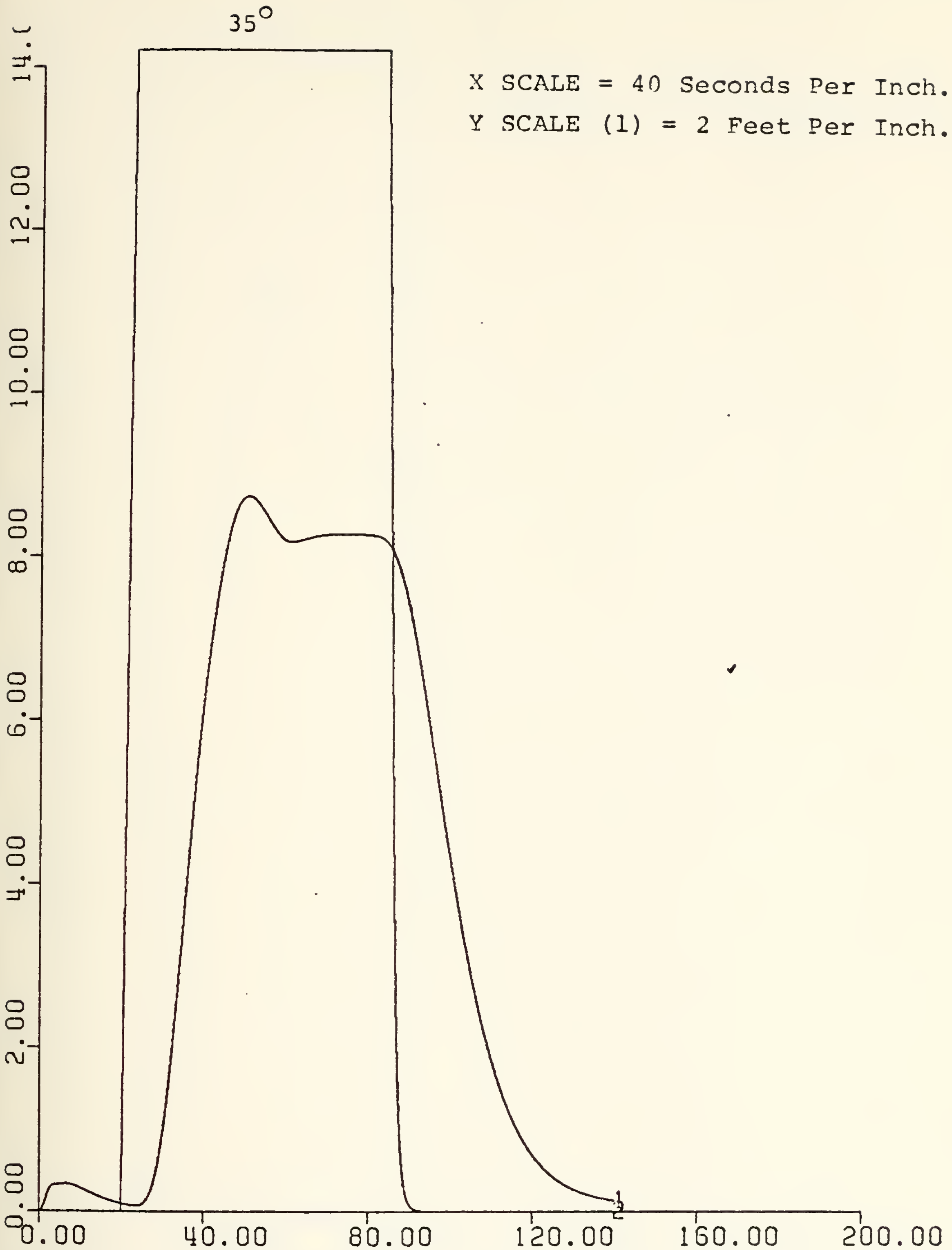


Figure 78.1. Depth vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 18 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°)

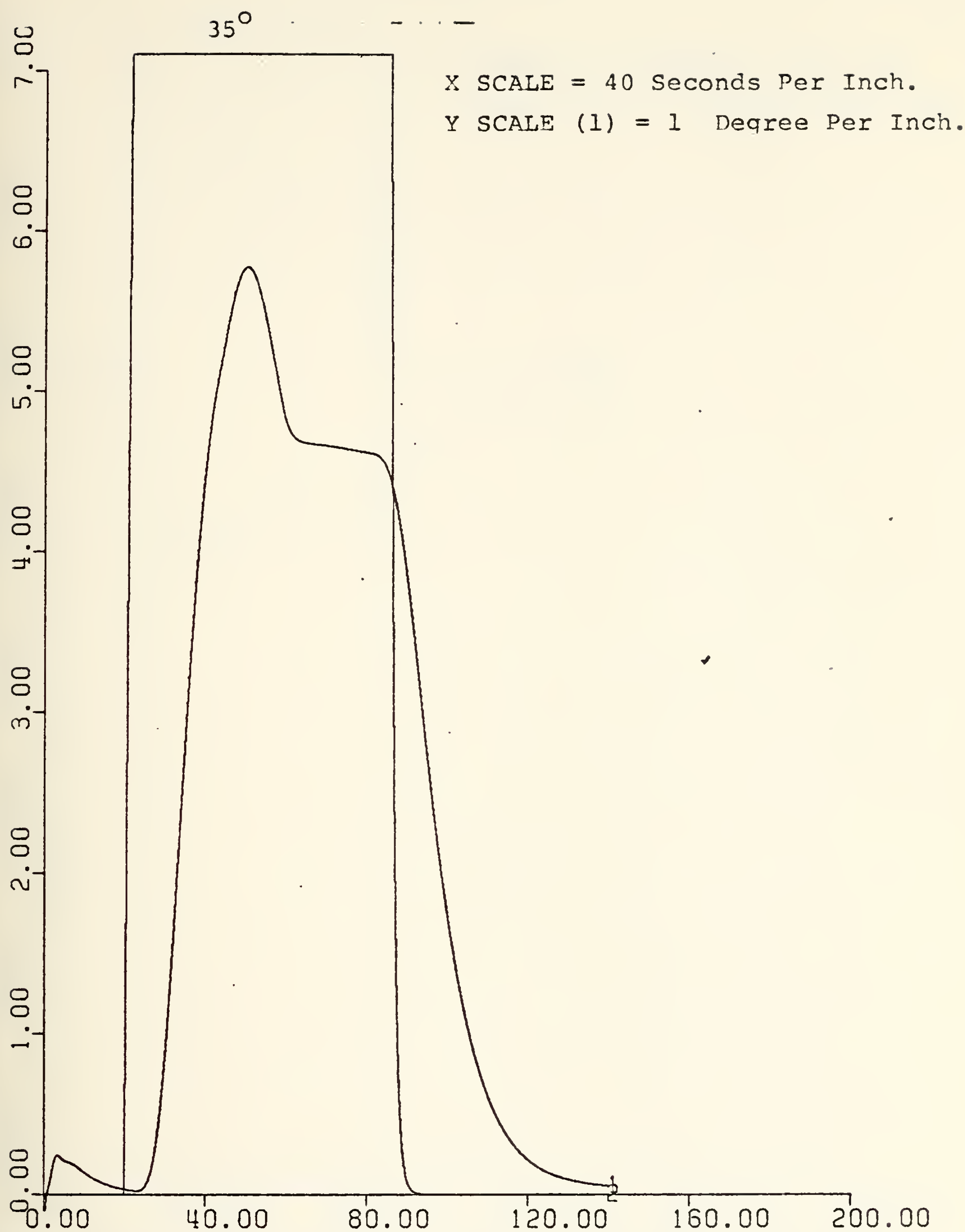


Figure 79.1. Pitch vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 18 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

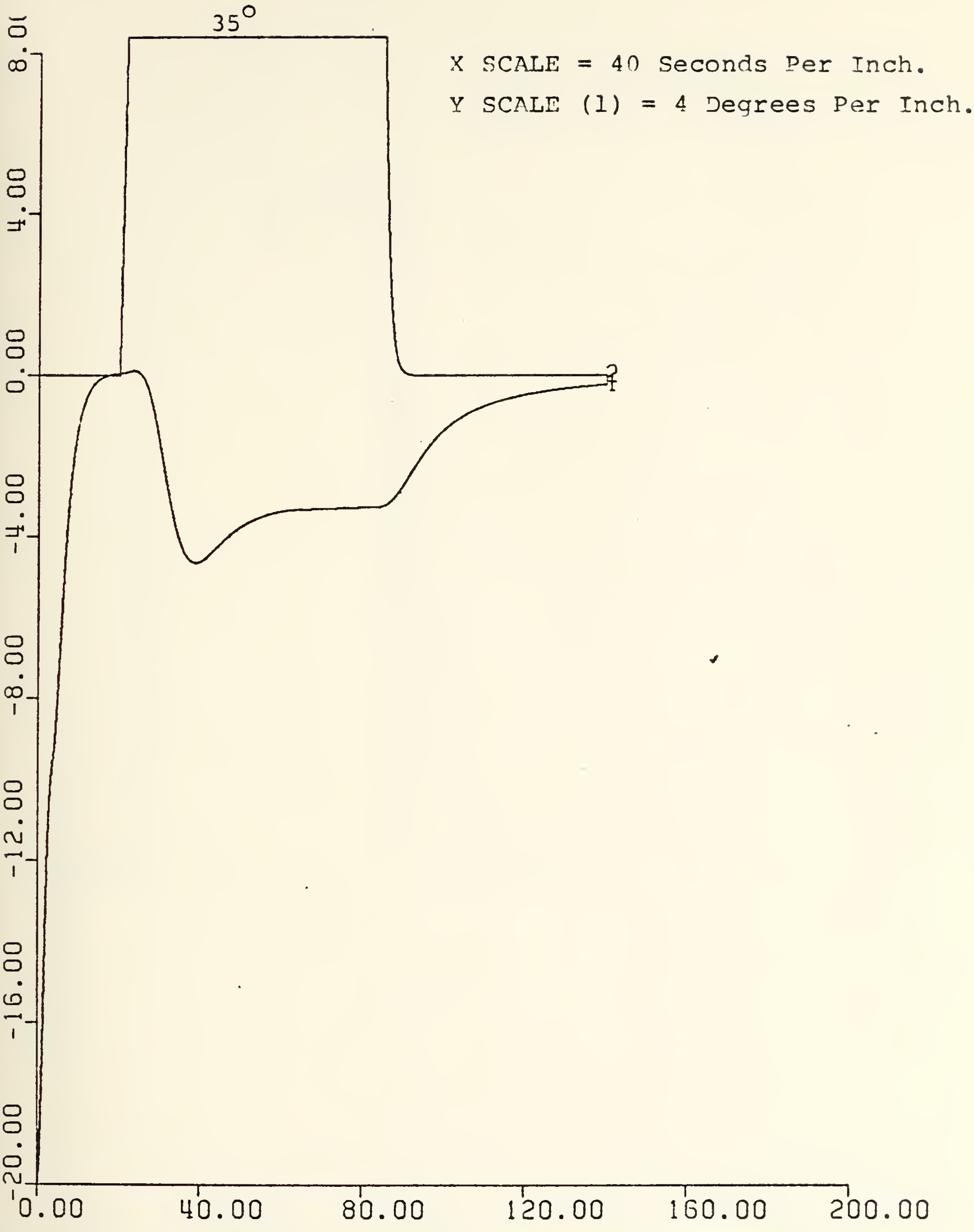


Figure 80.1. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 18 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

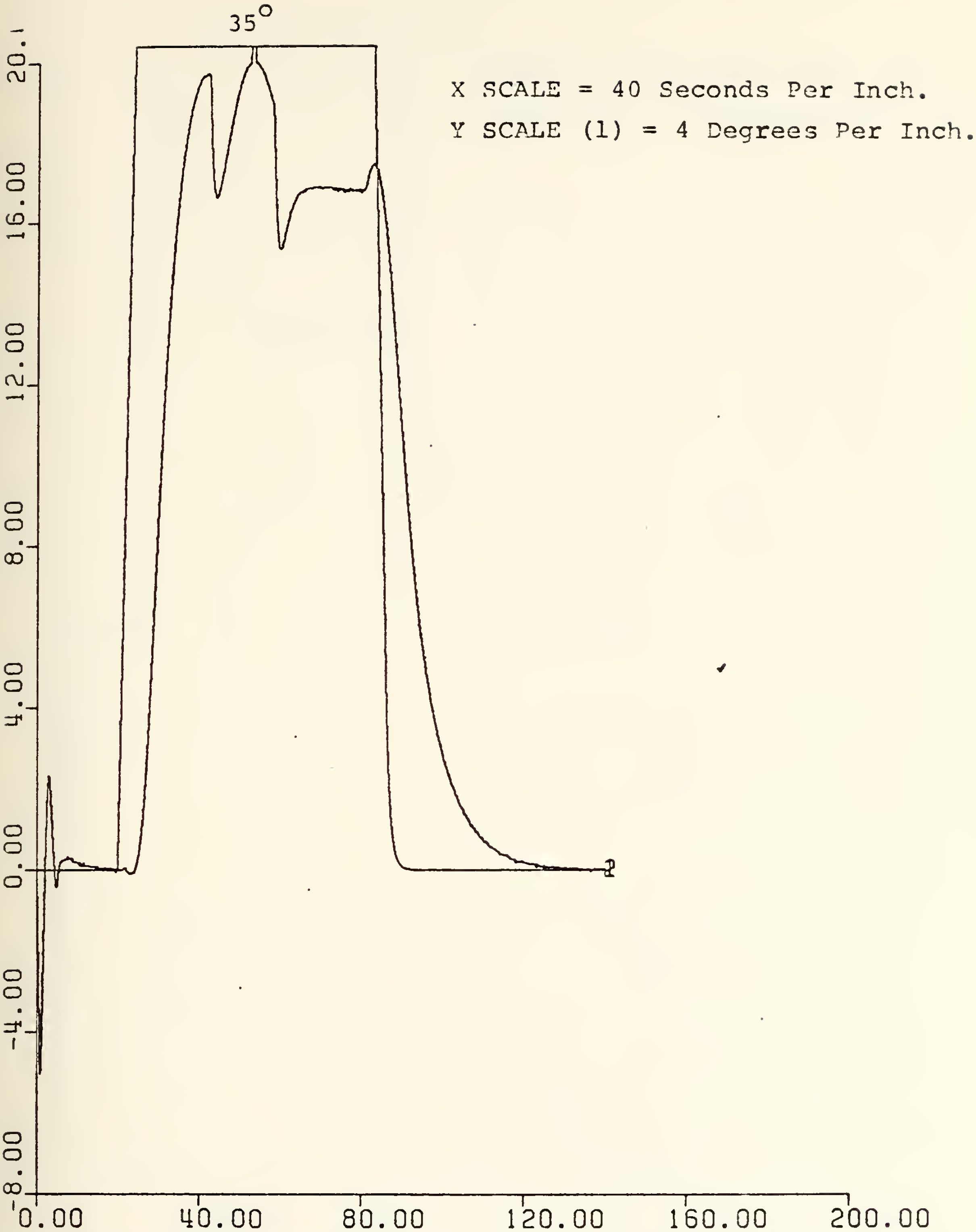


Figure 81.1. Sternplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 18 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

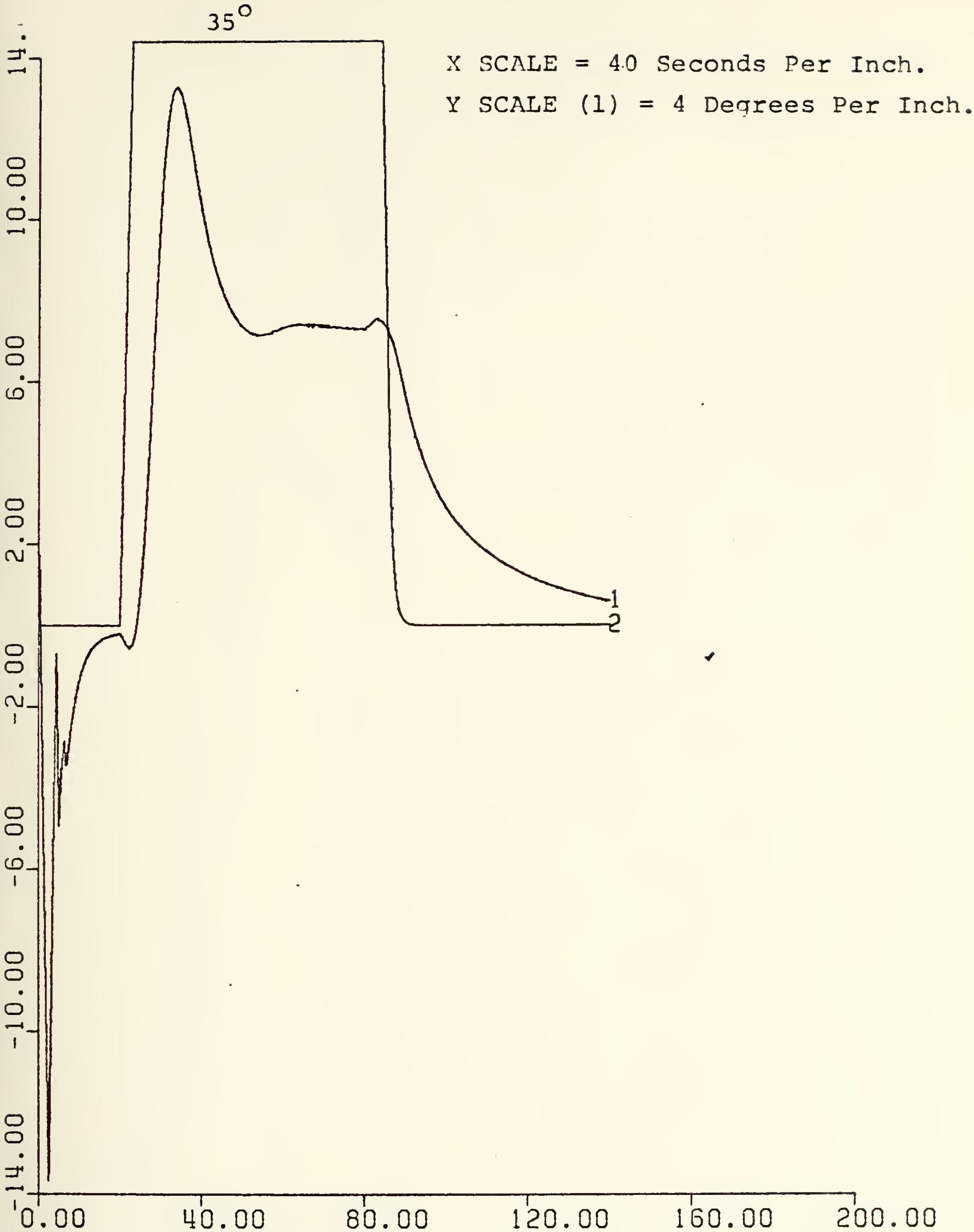


Figure 82.1. Sailplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 18 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

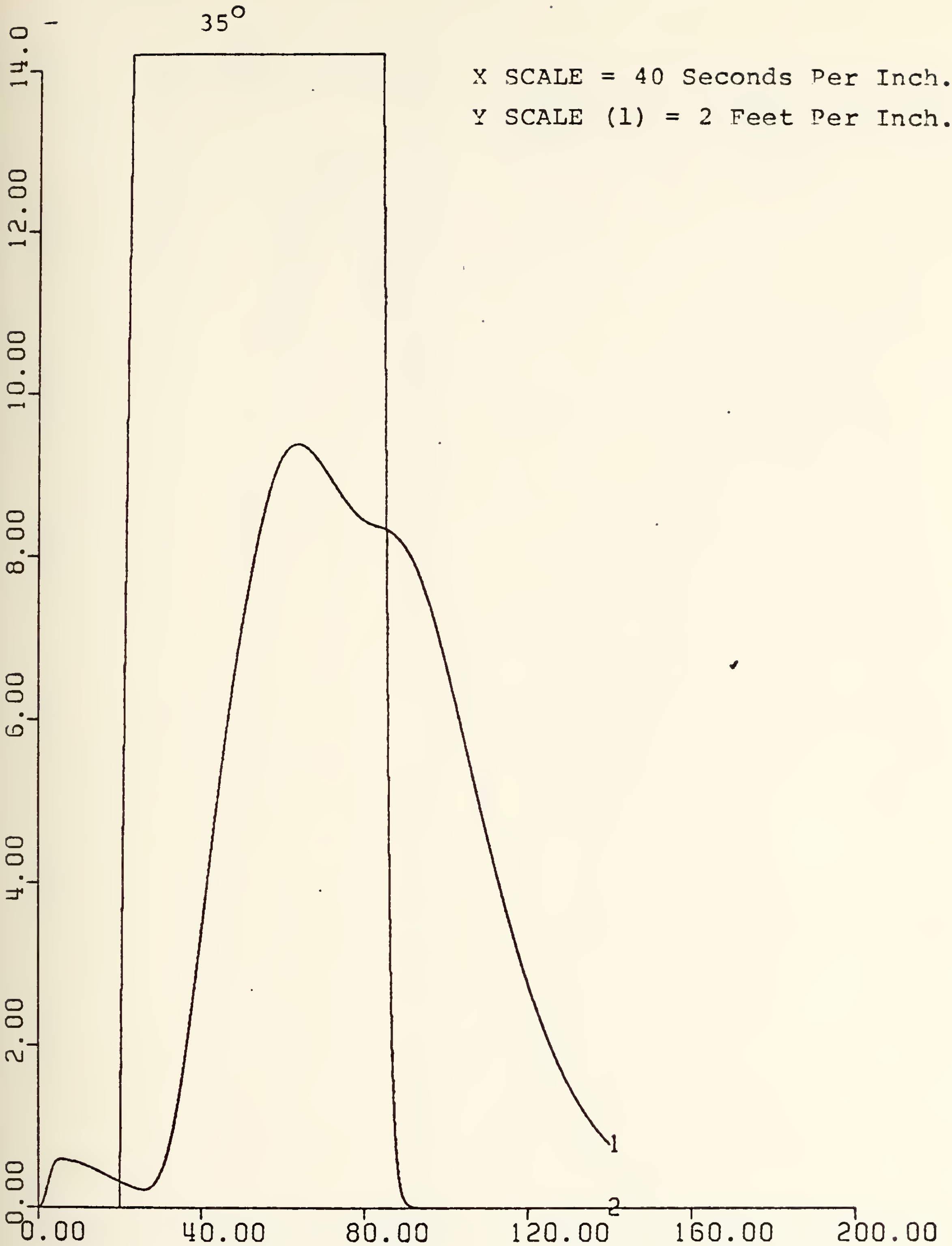


Figure 83.1. Depth vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 12 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

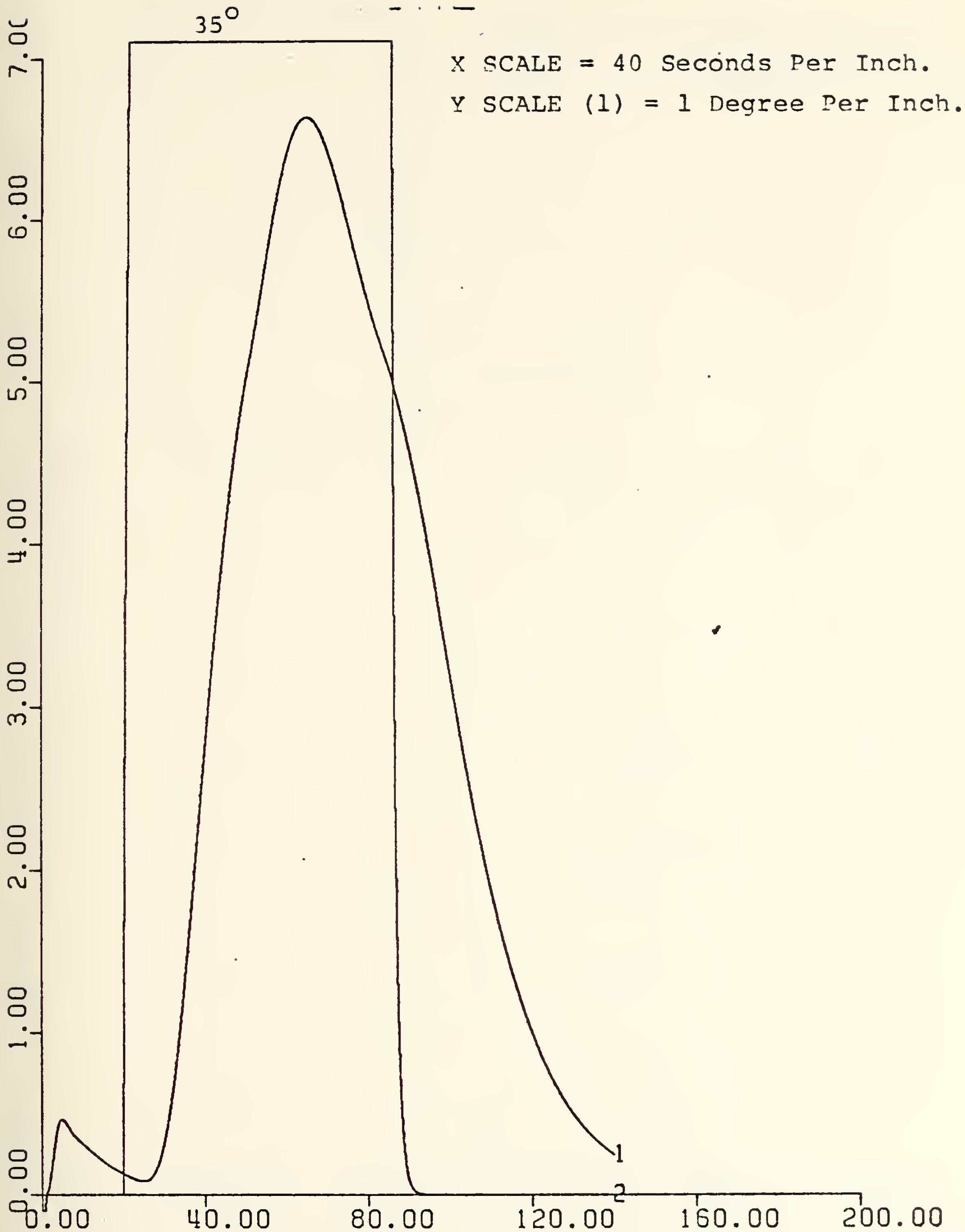


Figure 84.1. Pitch vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10, UCK = 12 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

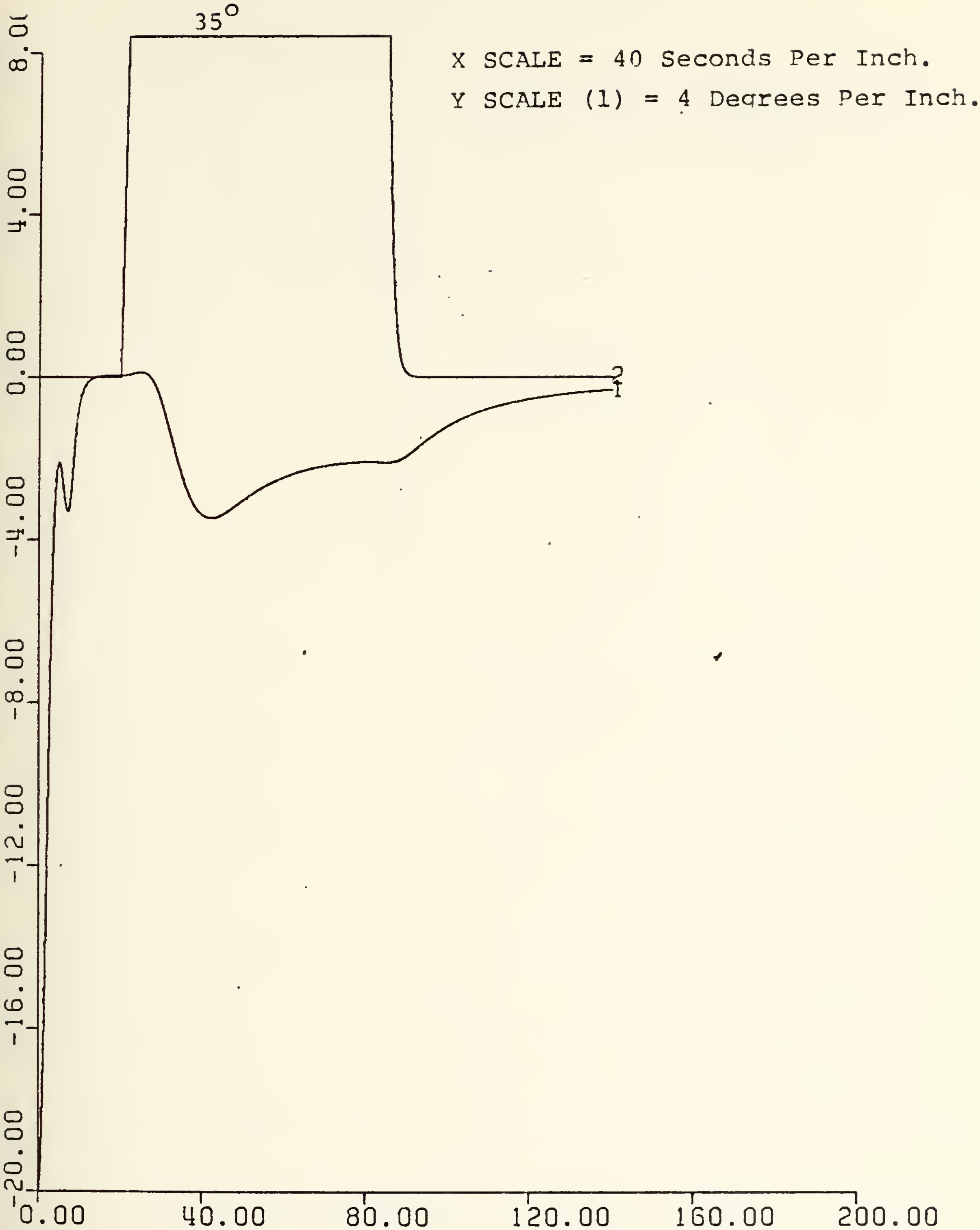


Figure 85.1. Roll vs. Time. Final Result With Roll Error Limiter K1 = 3, K2 = 10. UCK = 12 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

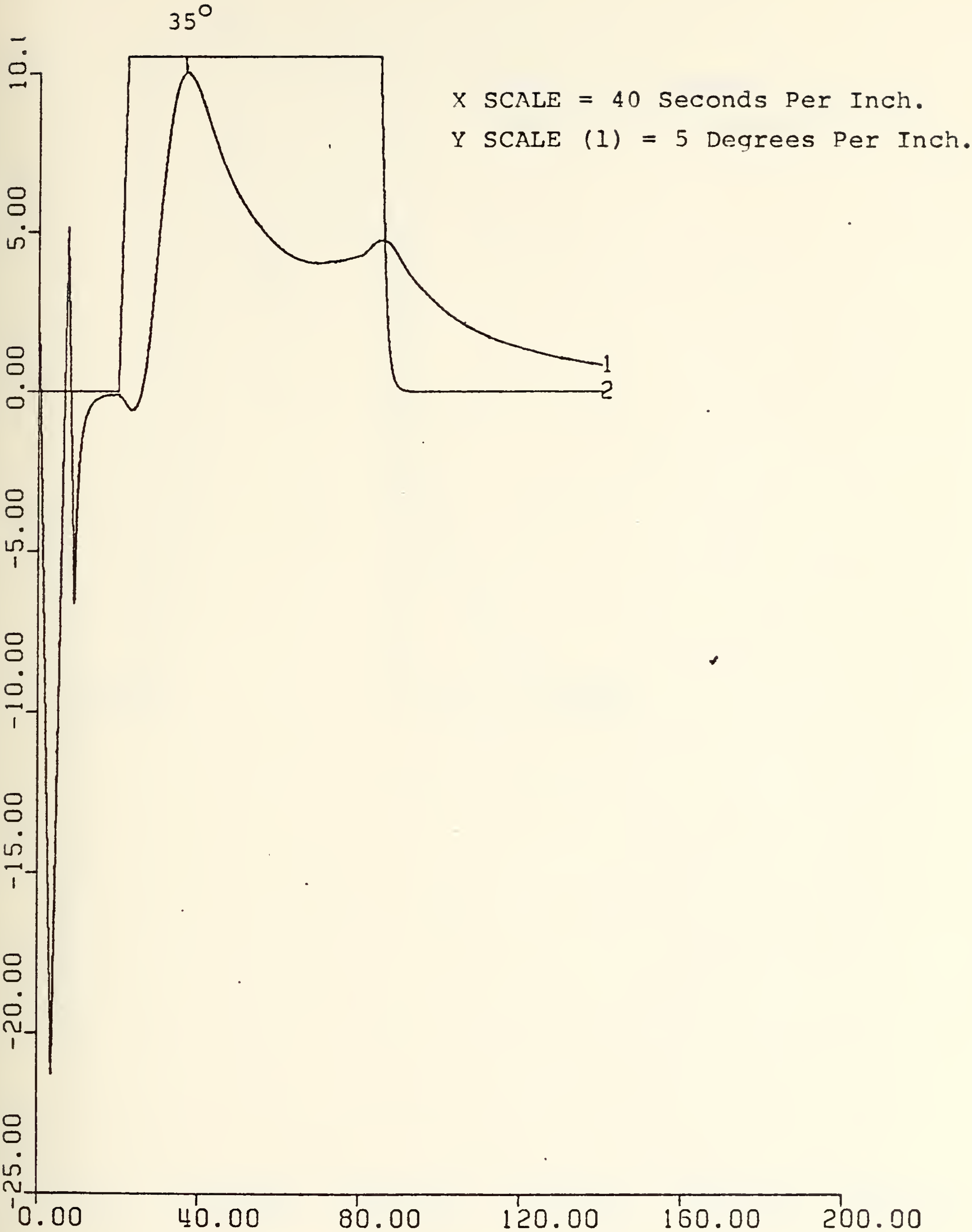


Figure 86.1. Sternplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 12 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

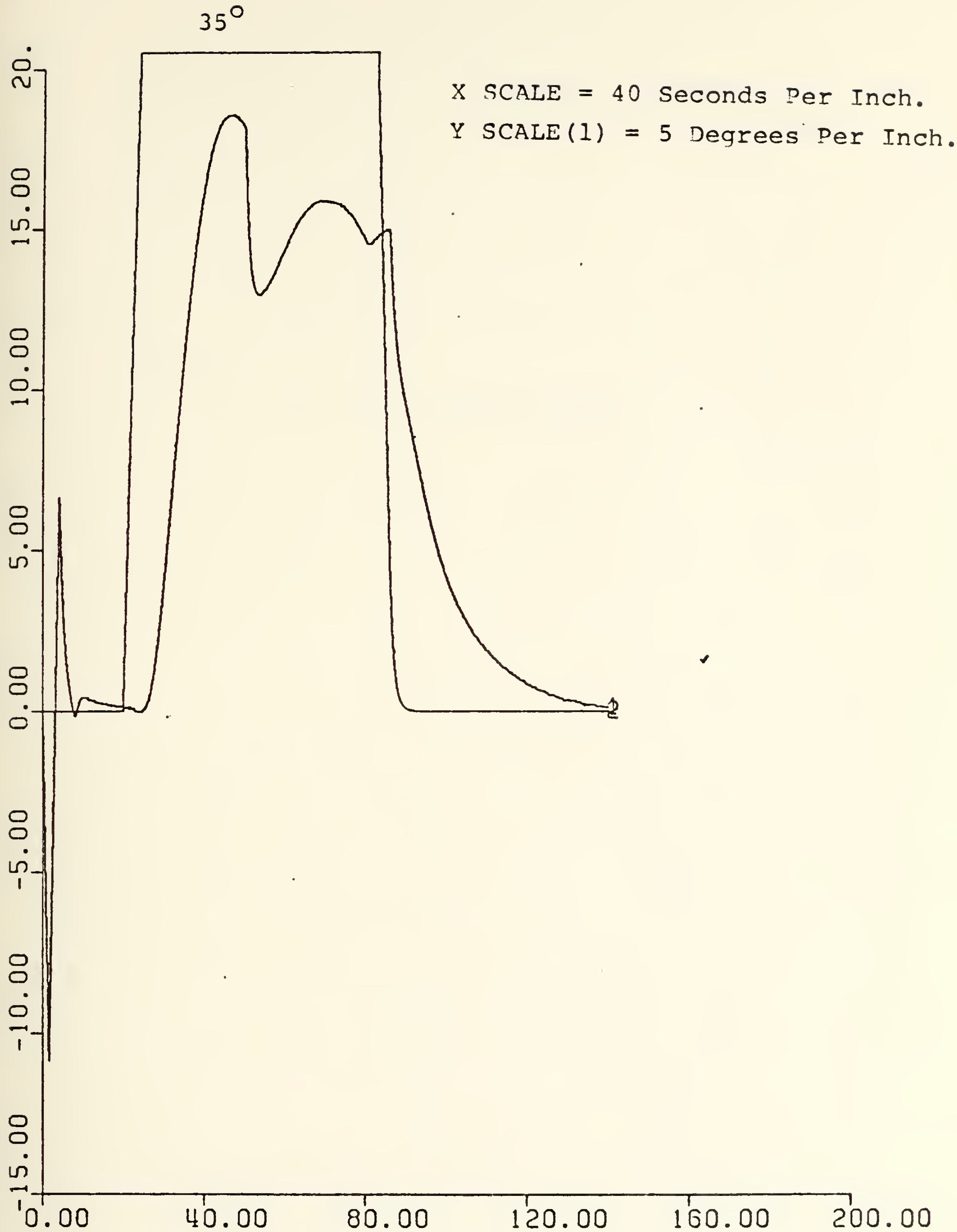


Figure 87.1. Sailplane vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 12 Knots. Initial Roll Angle = -20°.

.2. Rudder Response vs. Time (Rudder Ordered = 35°).

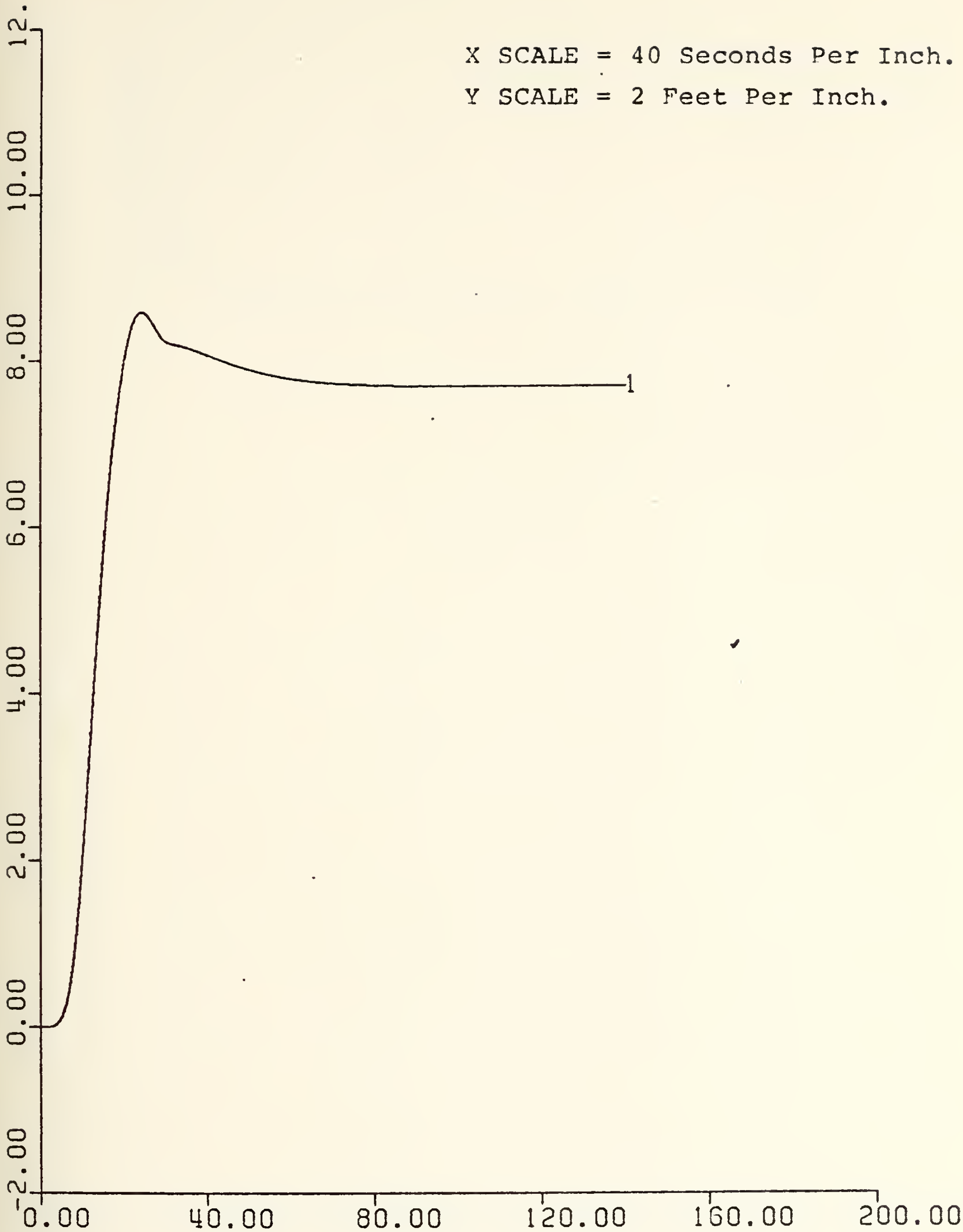


Figure 88. Depth vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

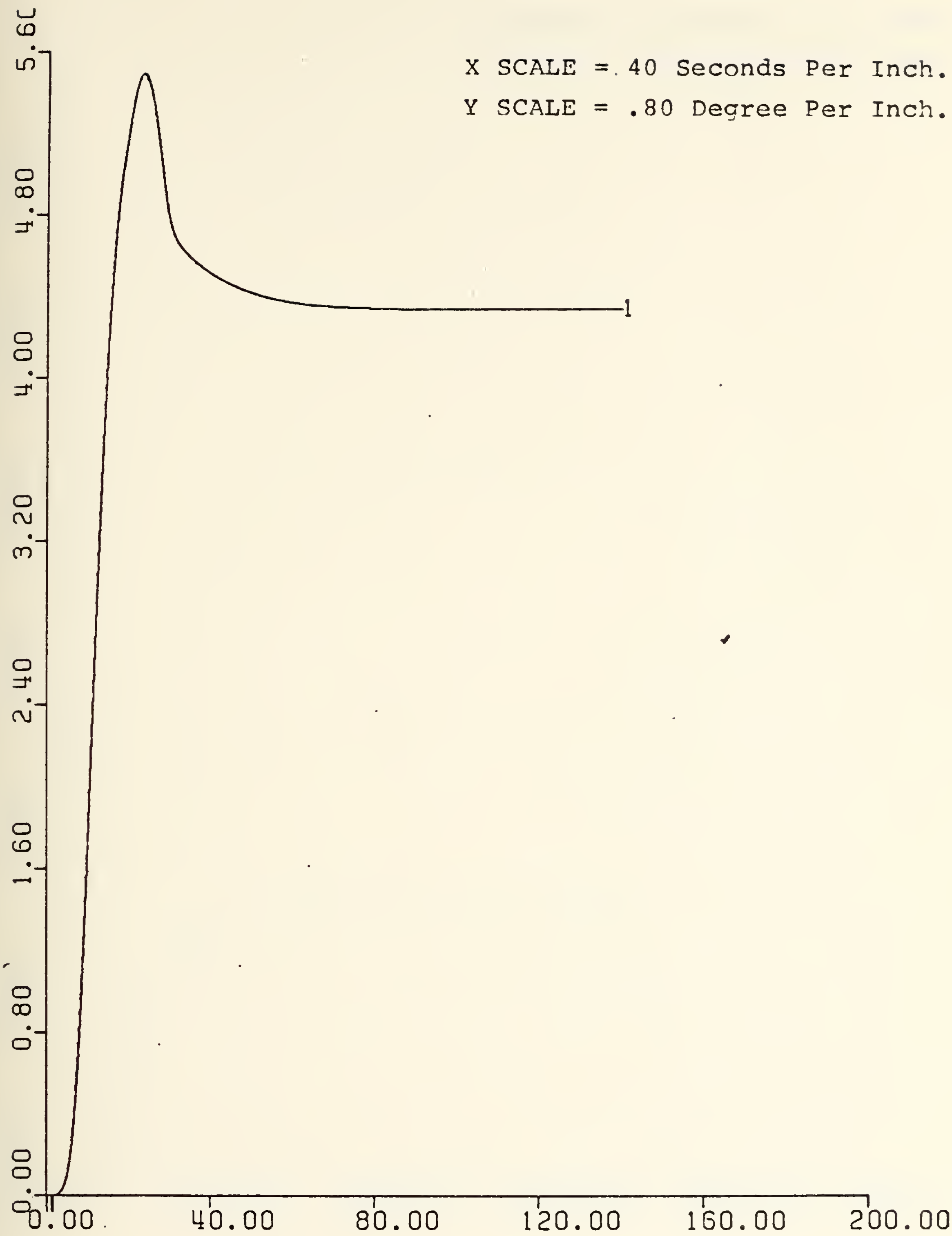


Figure 89. Pitch vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

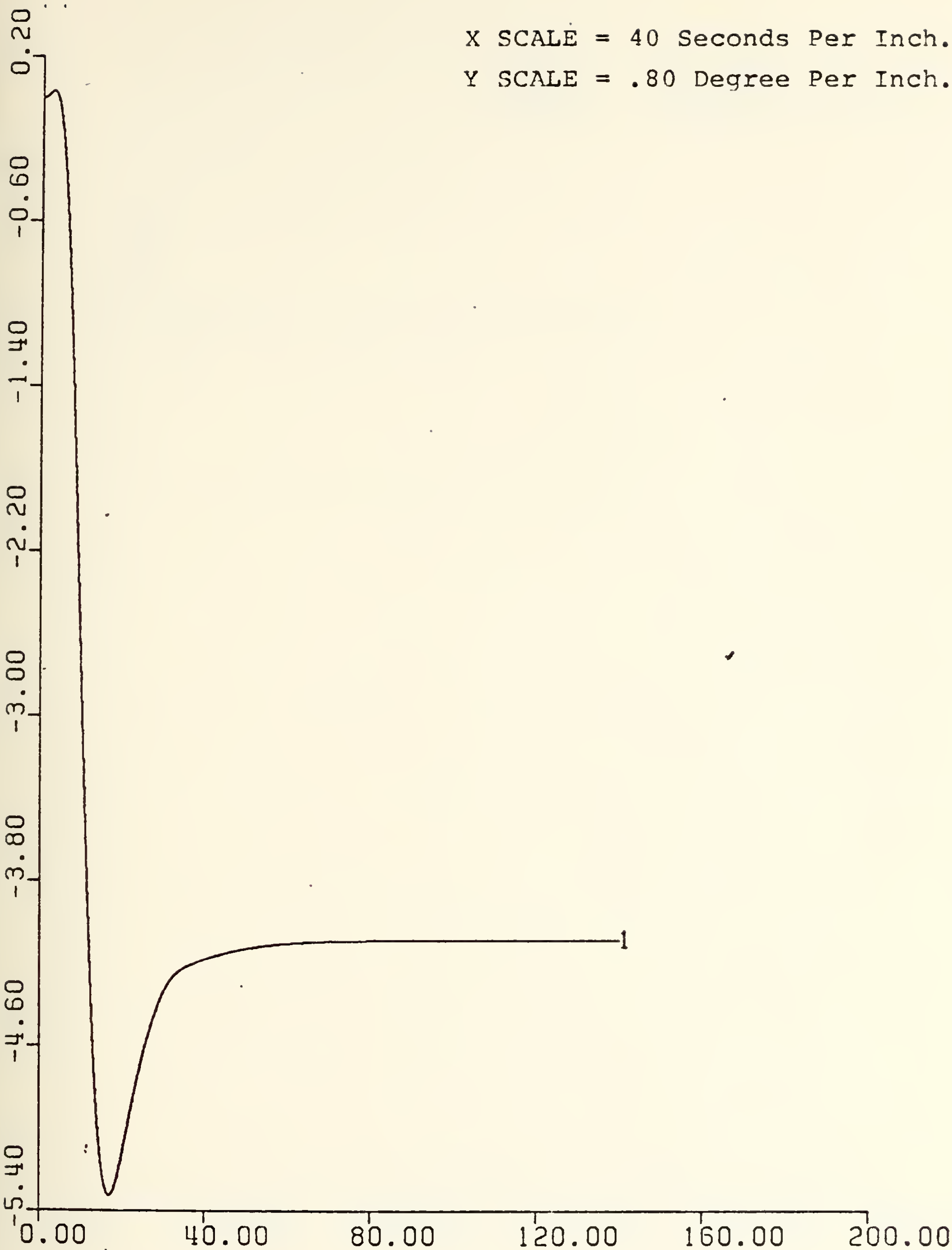


Figure 90. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

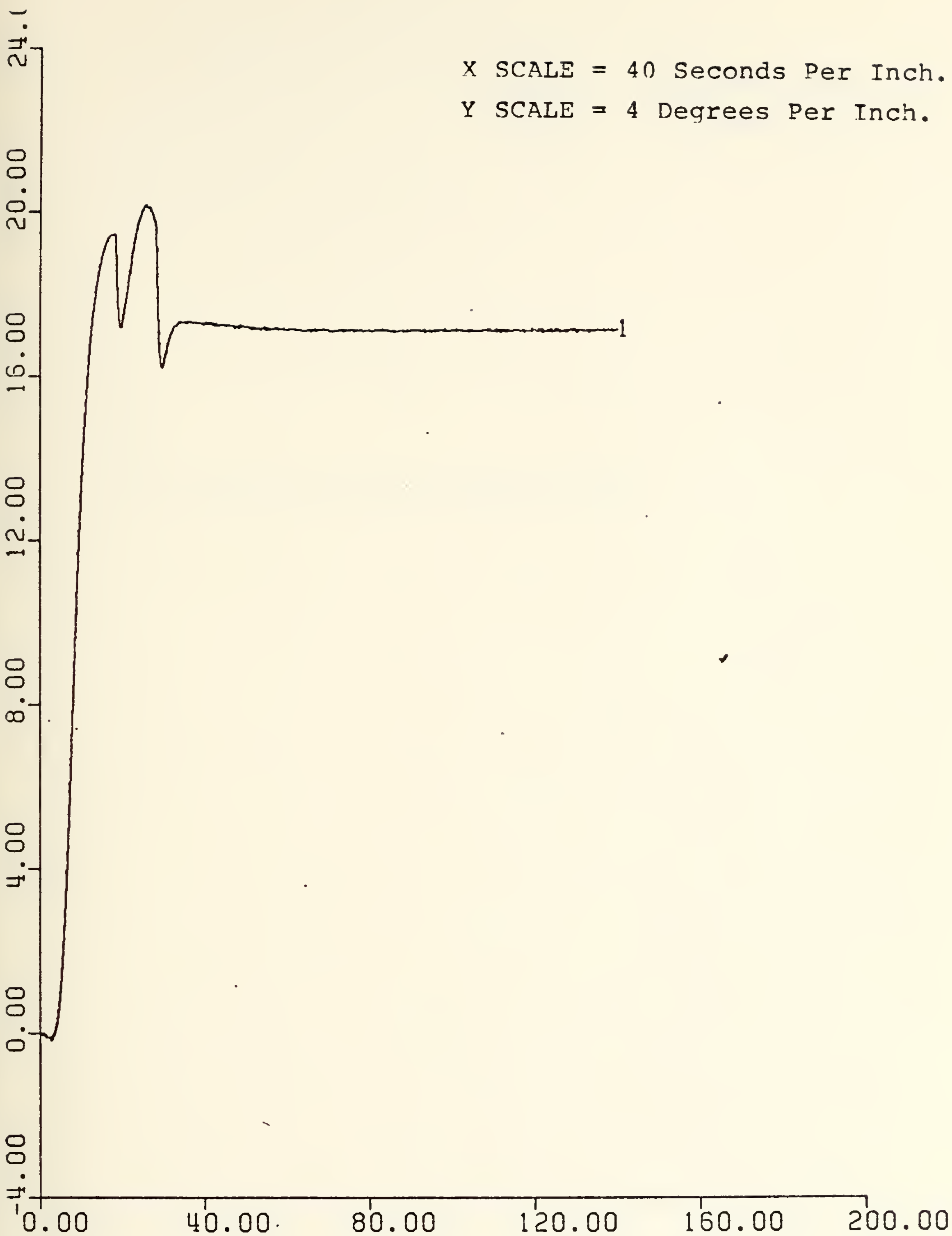


Figure 91. Sternplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

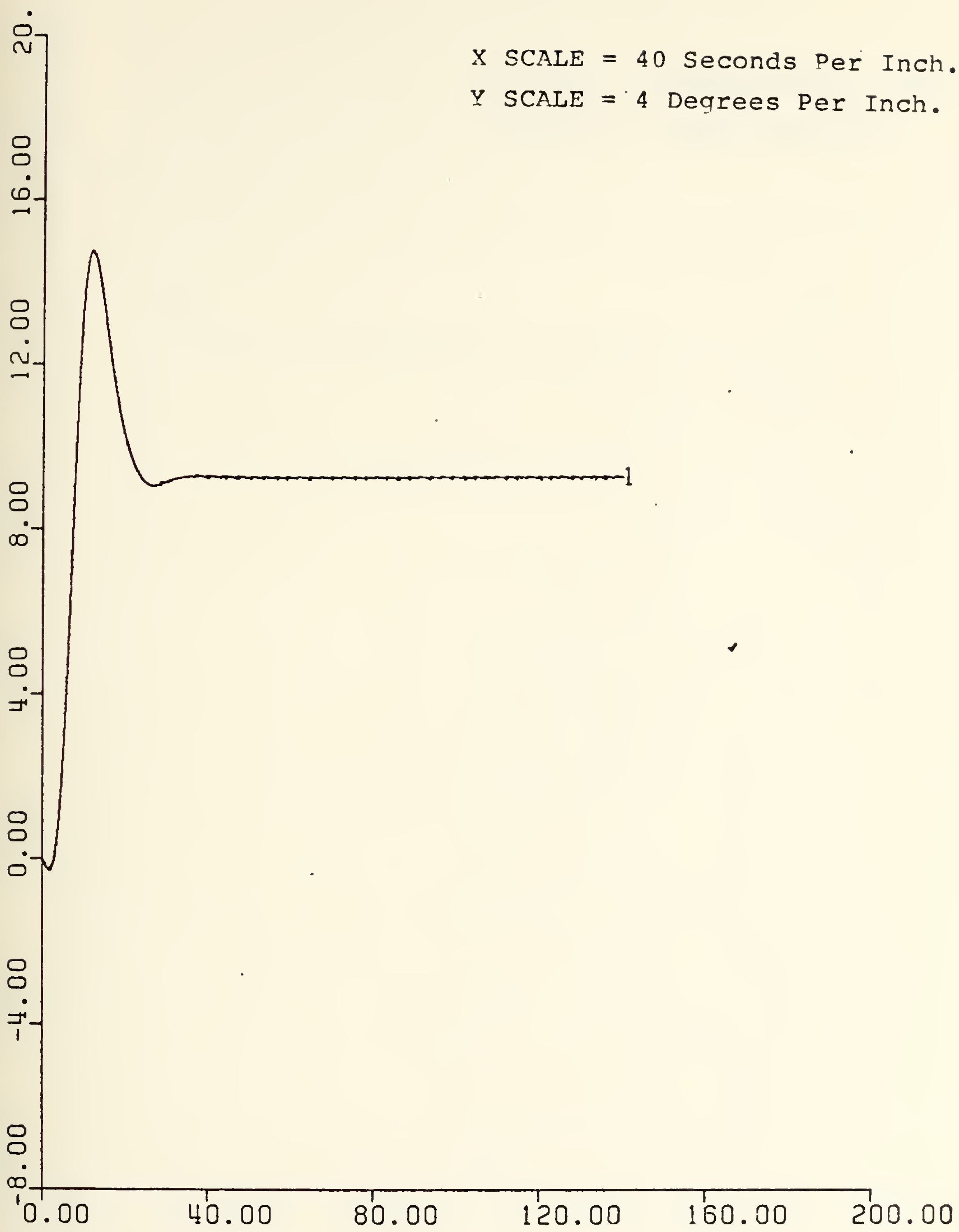


Figure 92. Sailplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

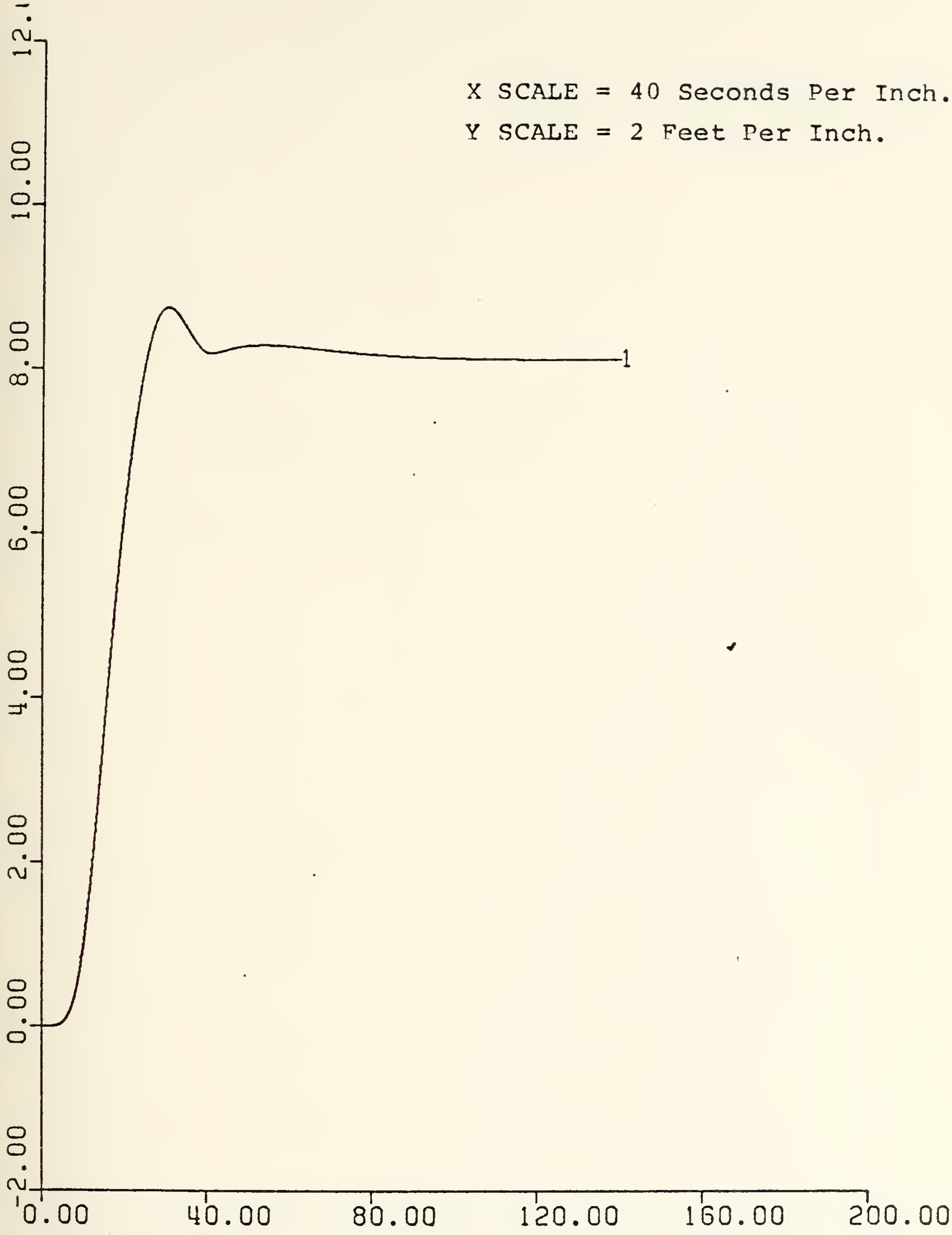
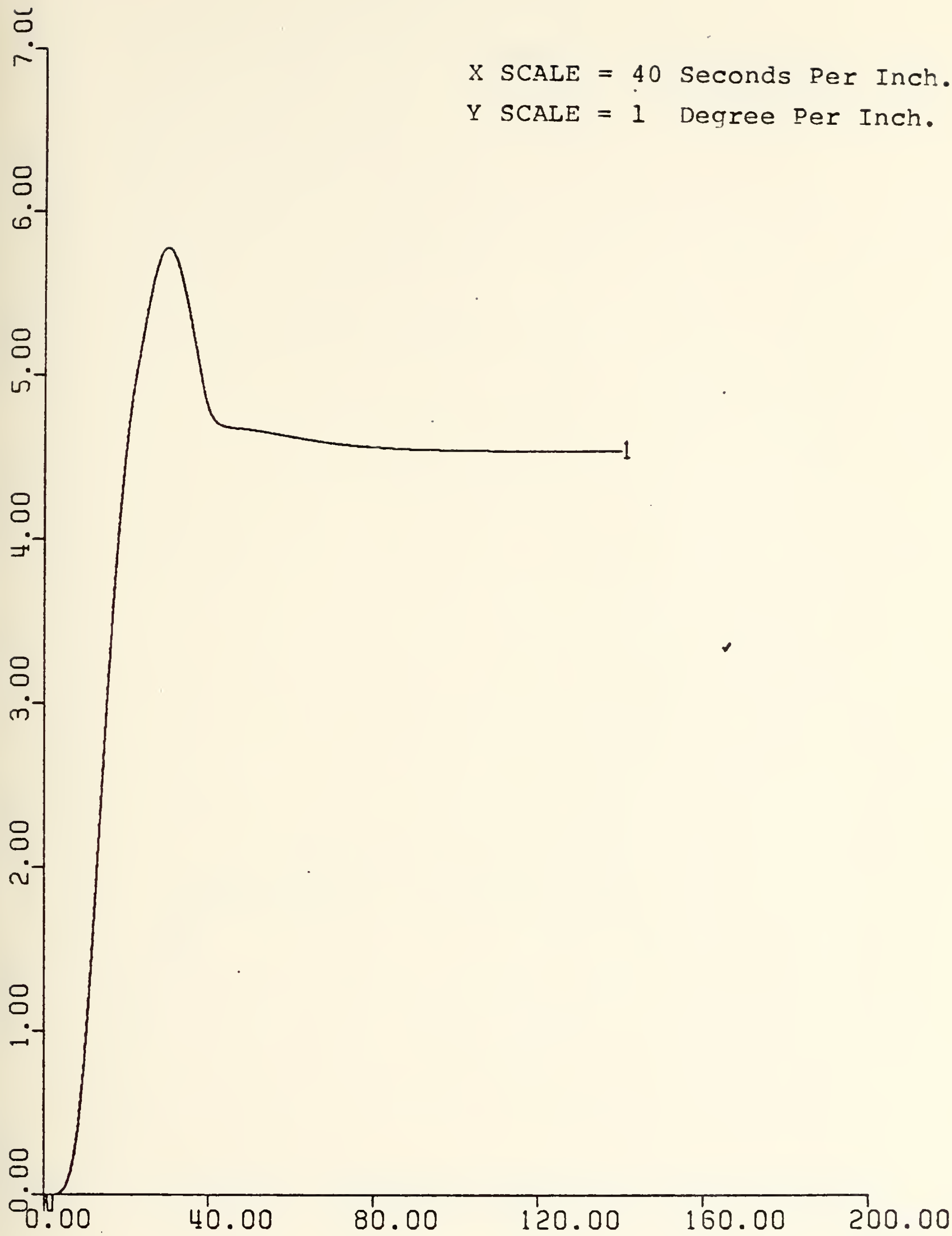


Figure 93. Depth vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 18 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.



Figire 94. Pitch vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 18 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

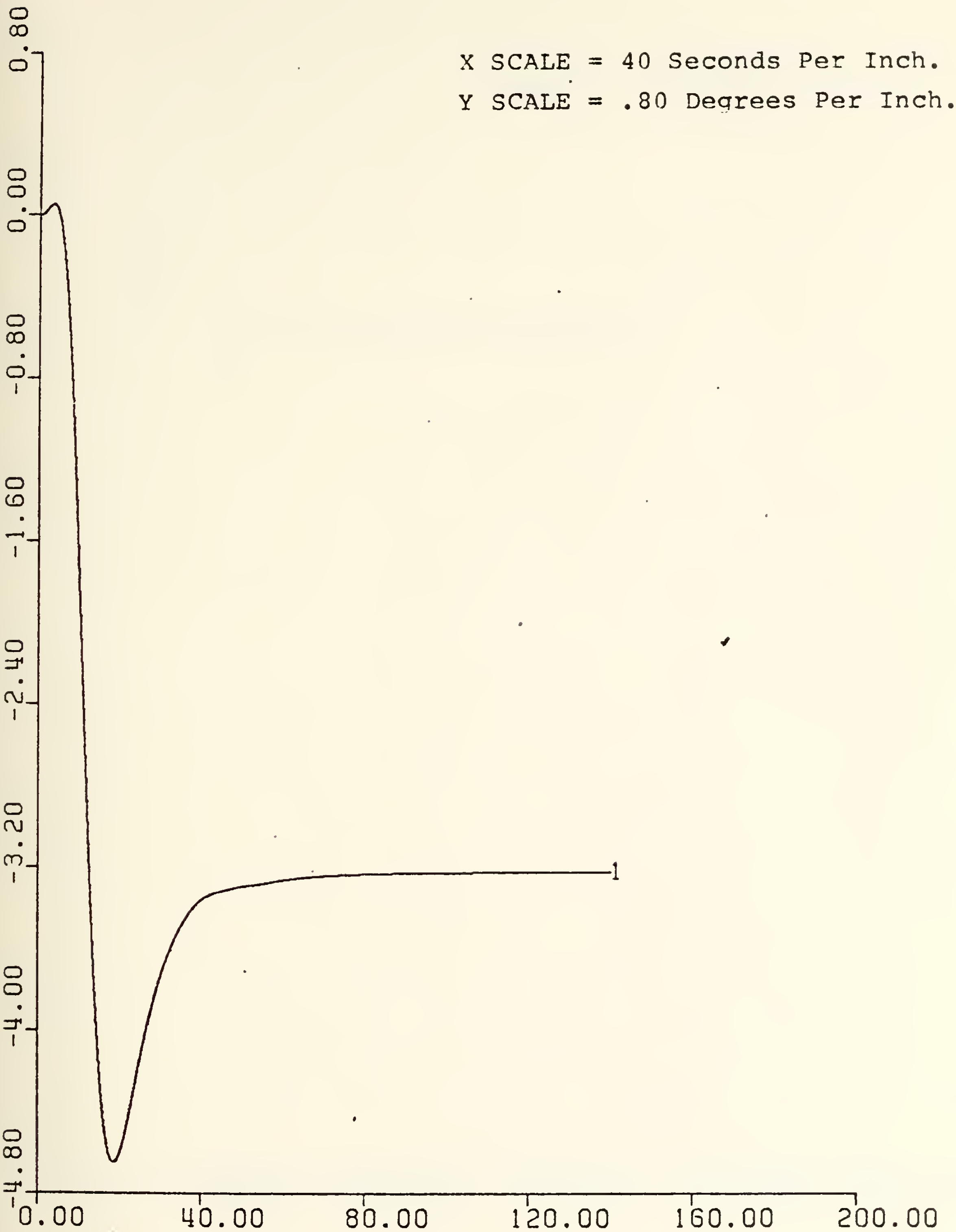


Figure 95. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 18 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

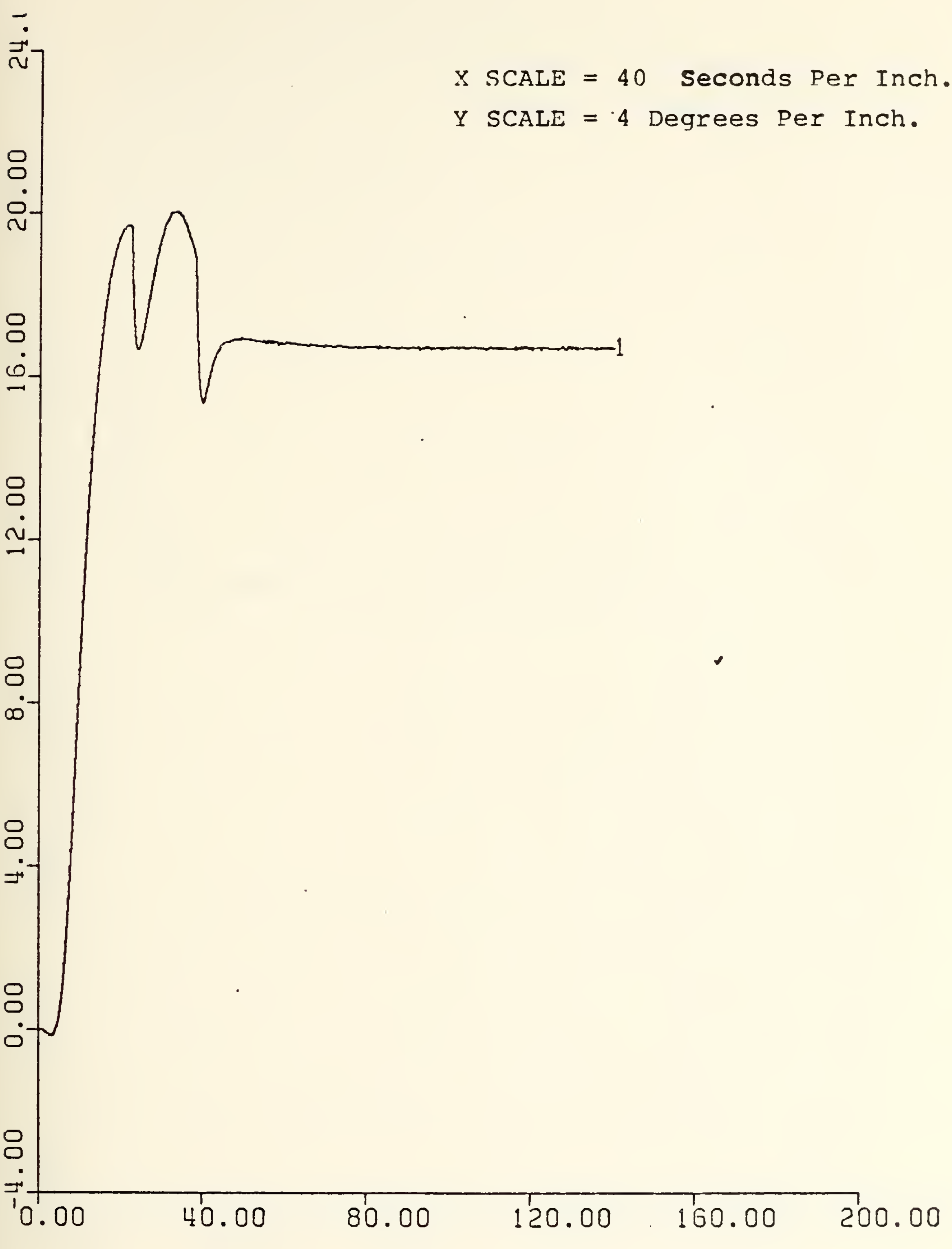


Figure 96. Sternplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 18 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

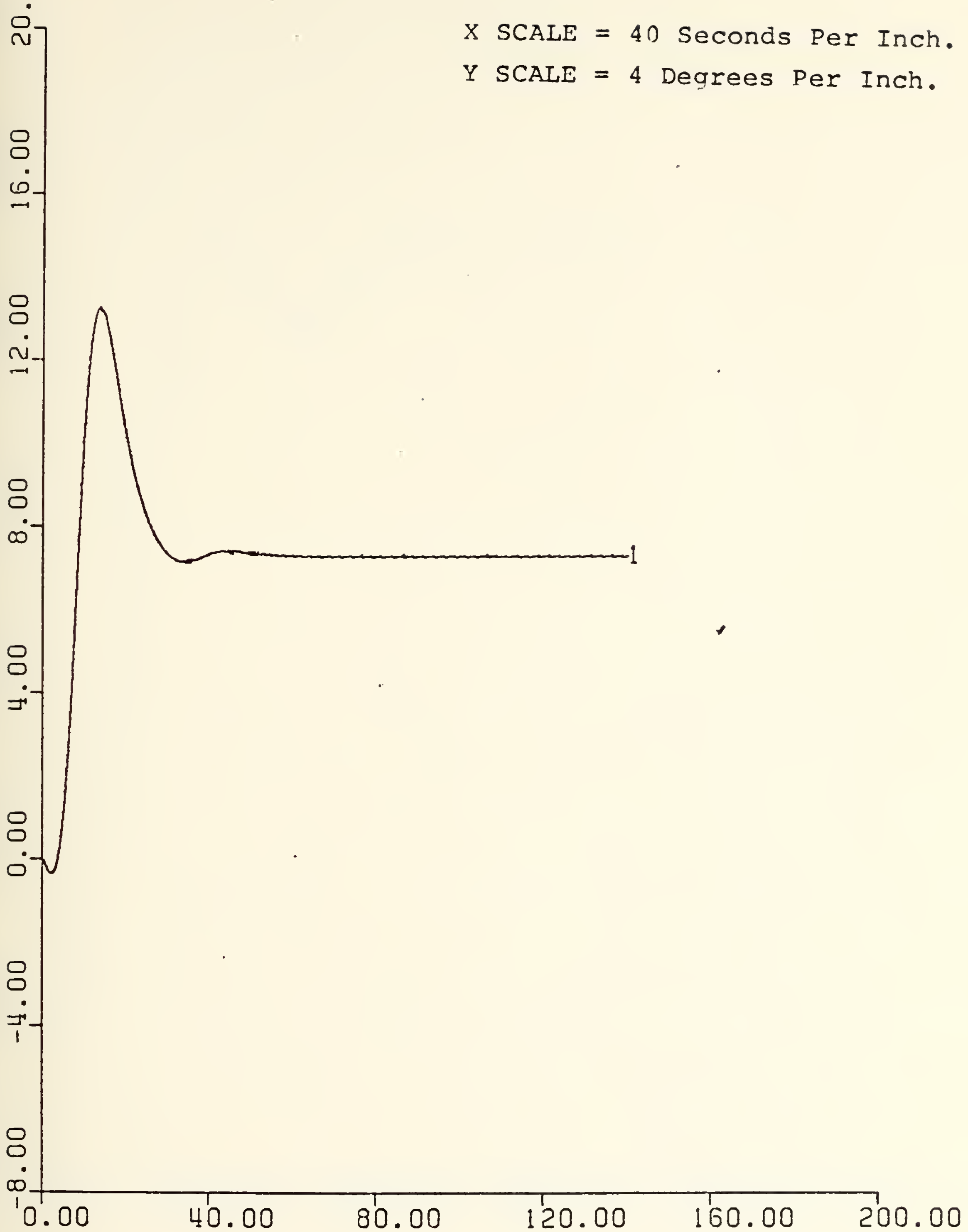


Figure 97. Sailplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 18 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

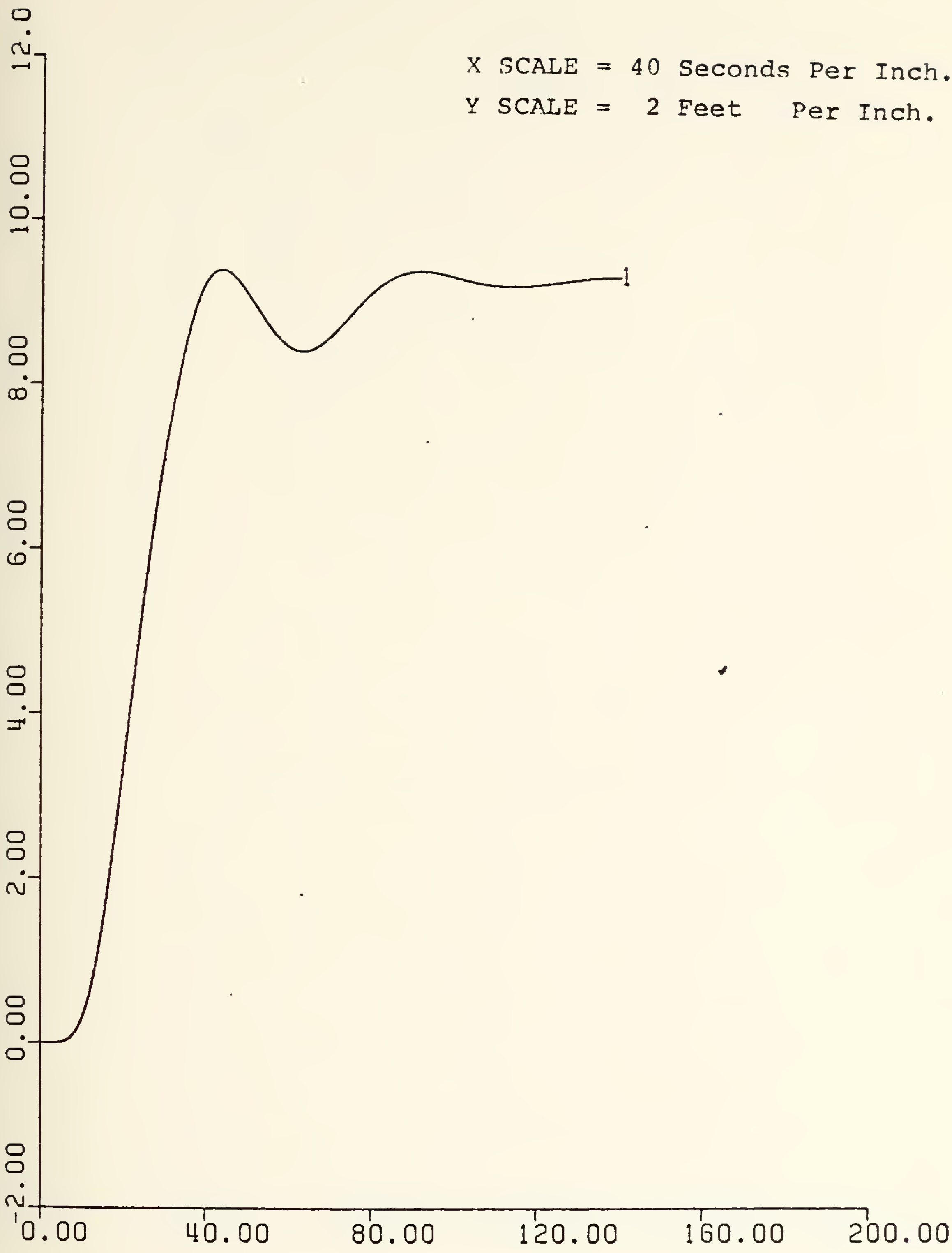


Figure 98. Depth vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 12 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

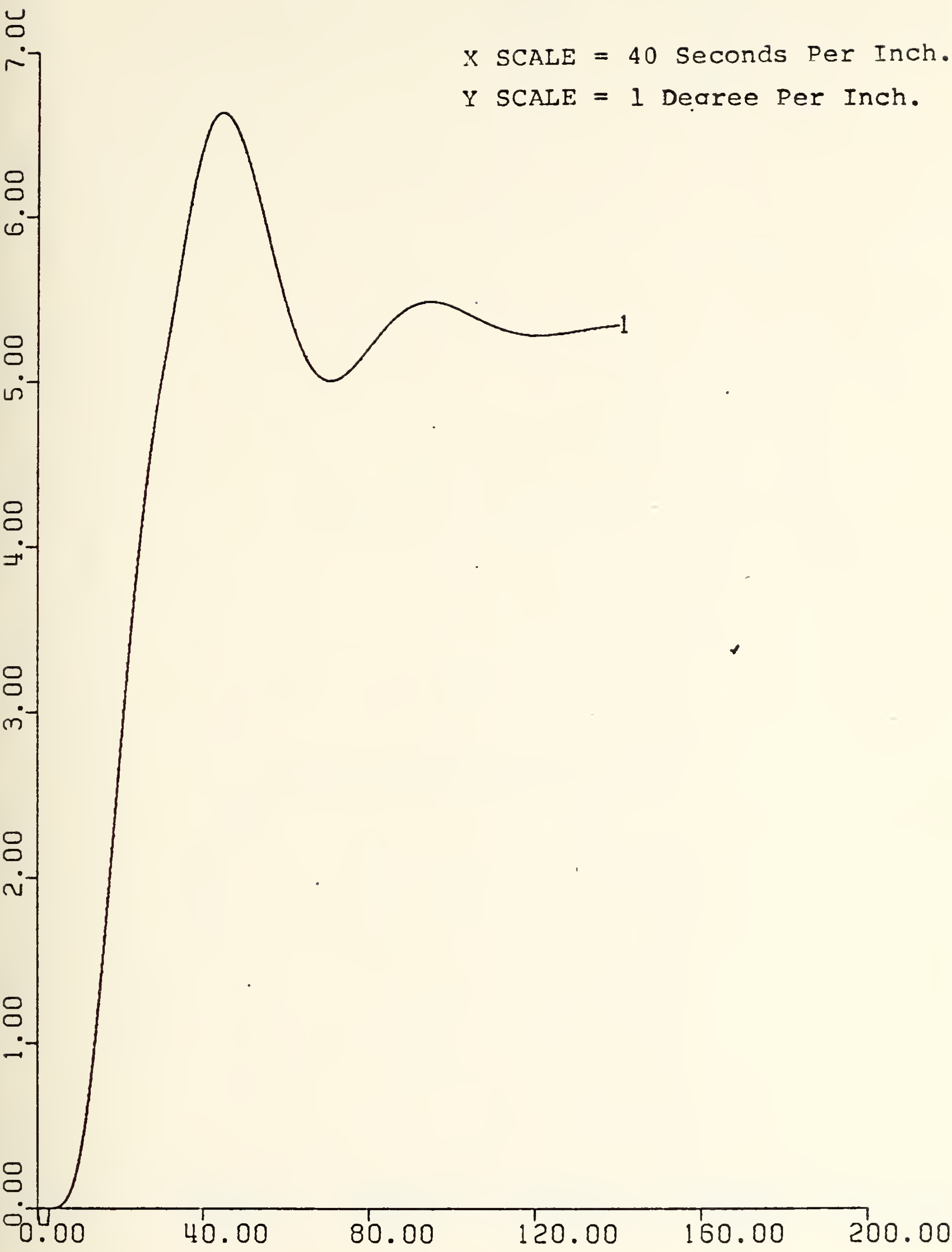


Figure 99. Pitch vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 12 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

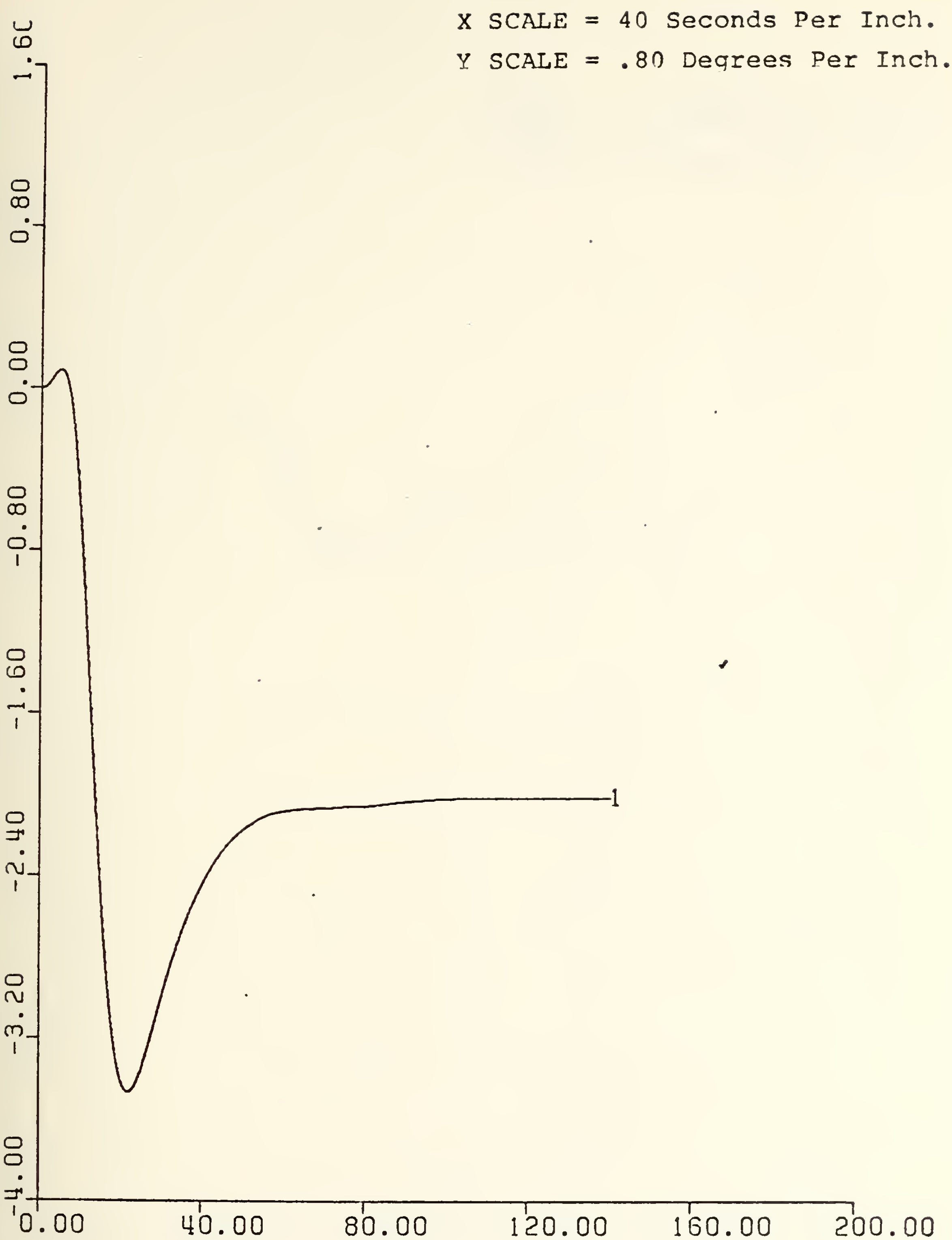


Figure 100. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 12 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

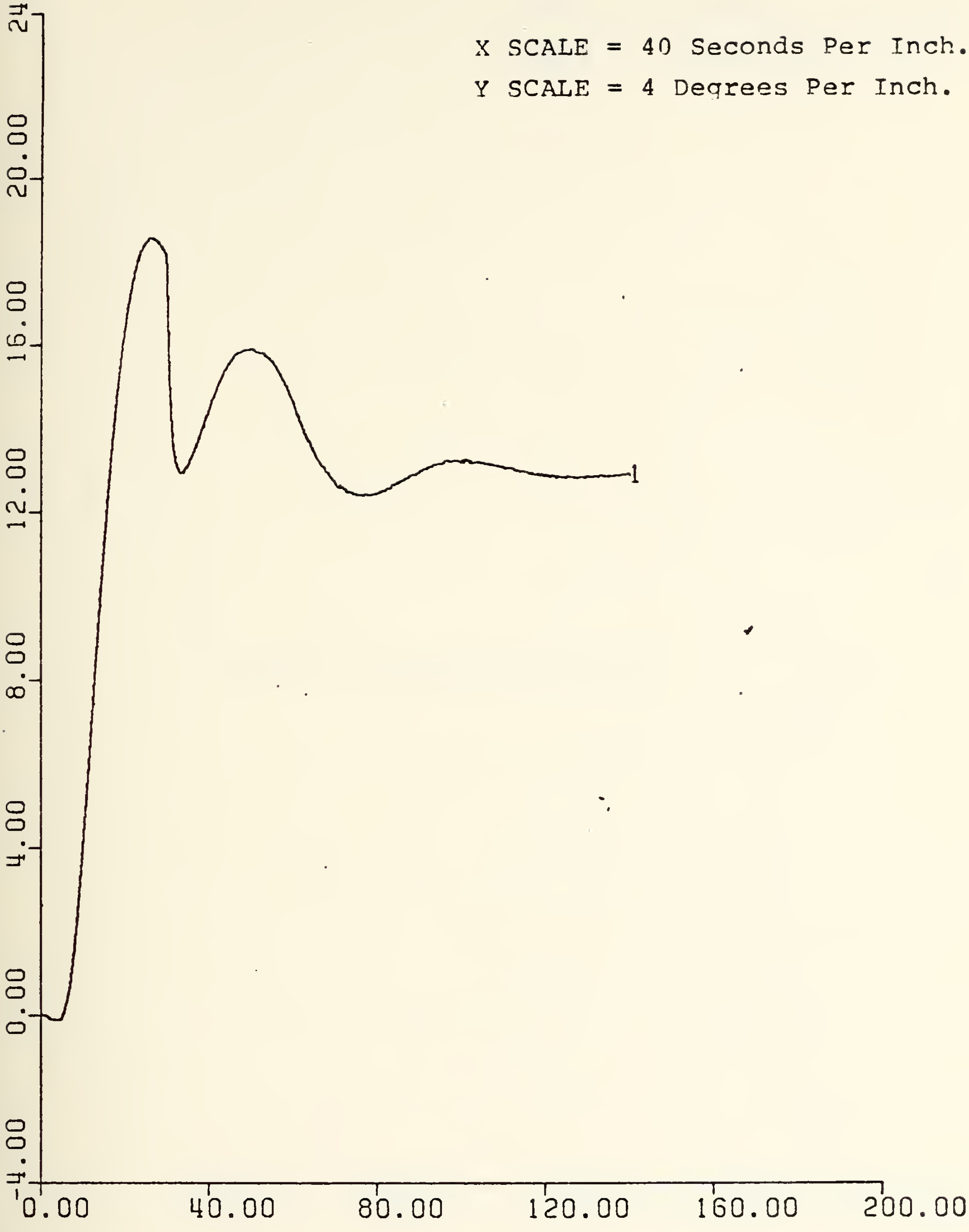


Figure 101. Sternplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 12 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

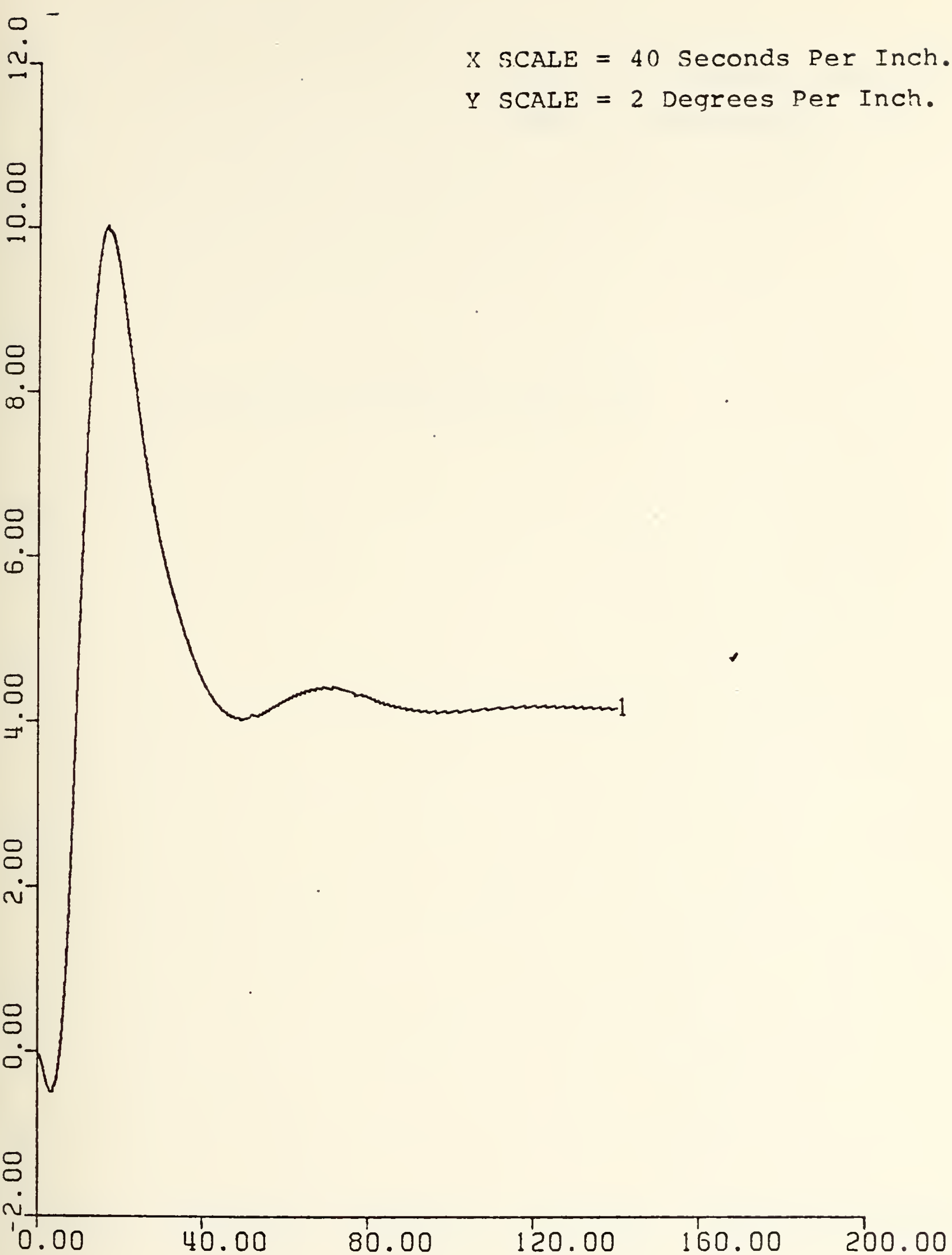


Figure 102. Sailplane Angle vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 12 Knots. Rudder Ordered = 35°. Initial Roll Angle = 0°.

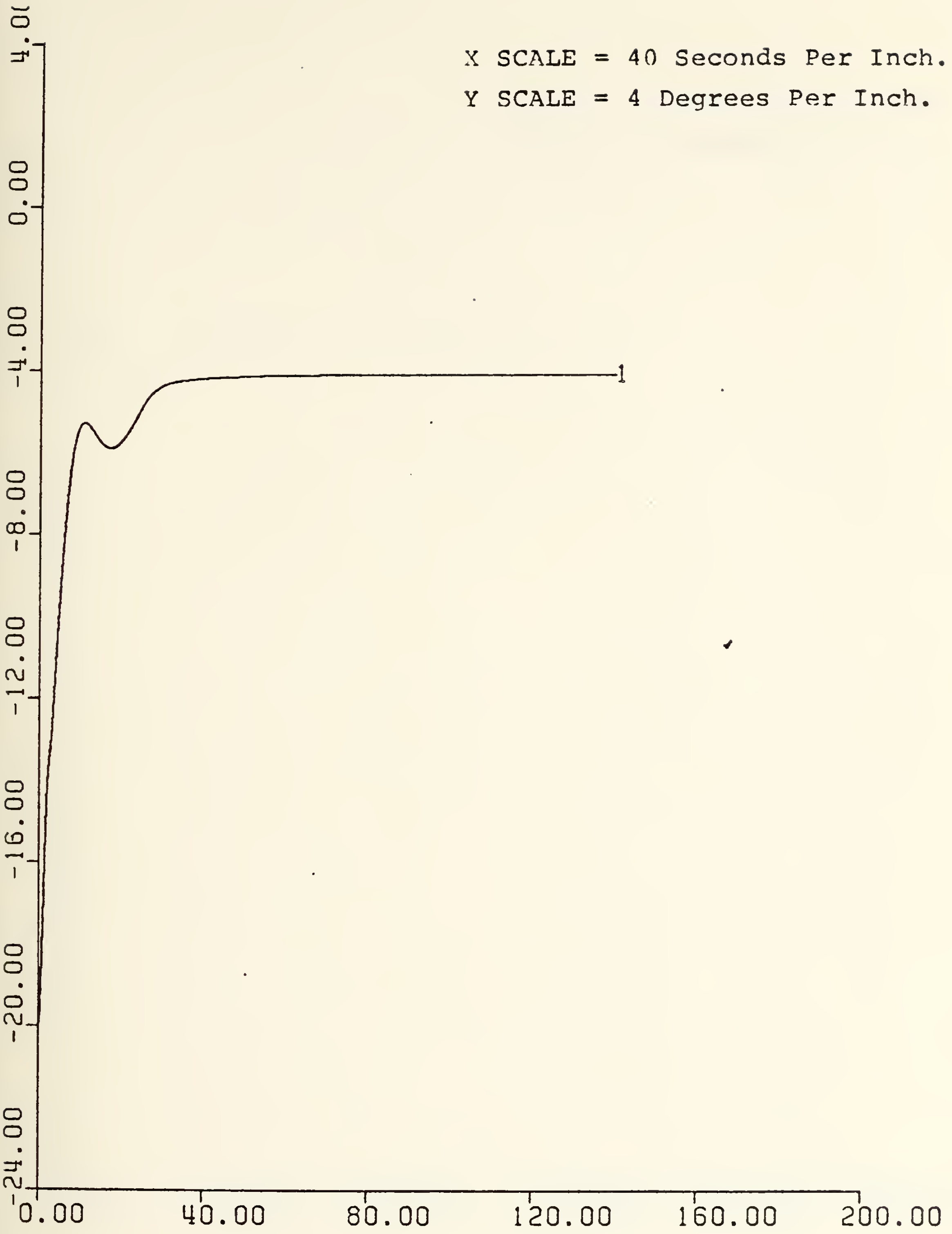


Figure 103. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 24 Knots. Rudder Ordered = 35°. Initial Roll Angle = -20°.

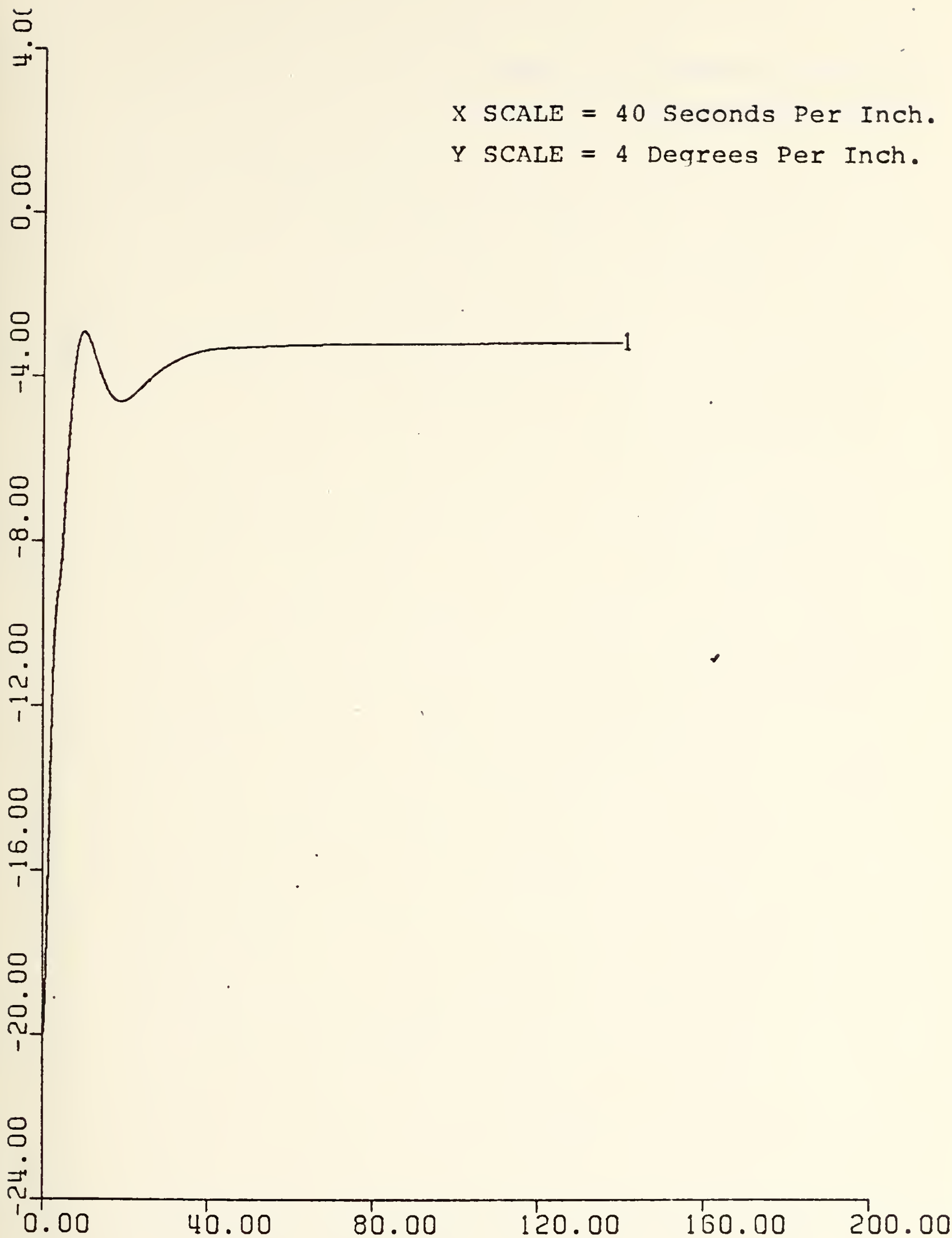


Figure 104. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 18 Knots. Rudder Ordered = 35°. Initial Roll Angle = -20°.

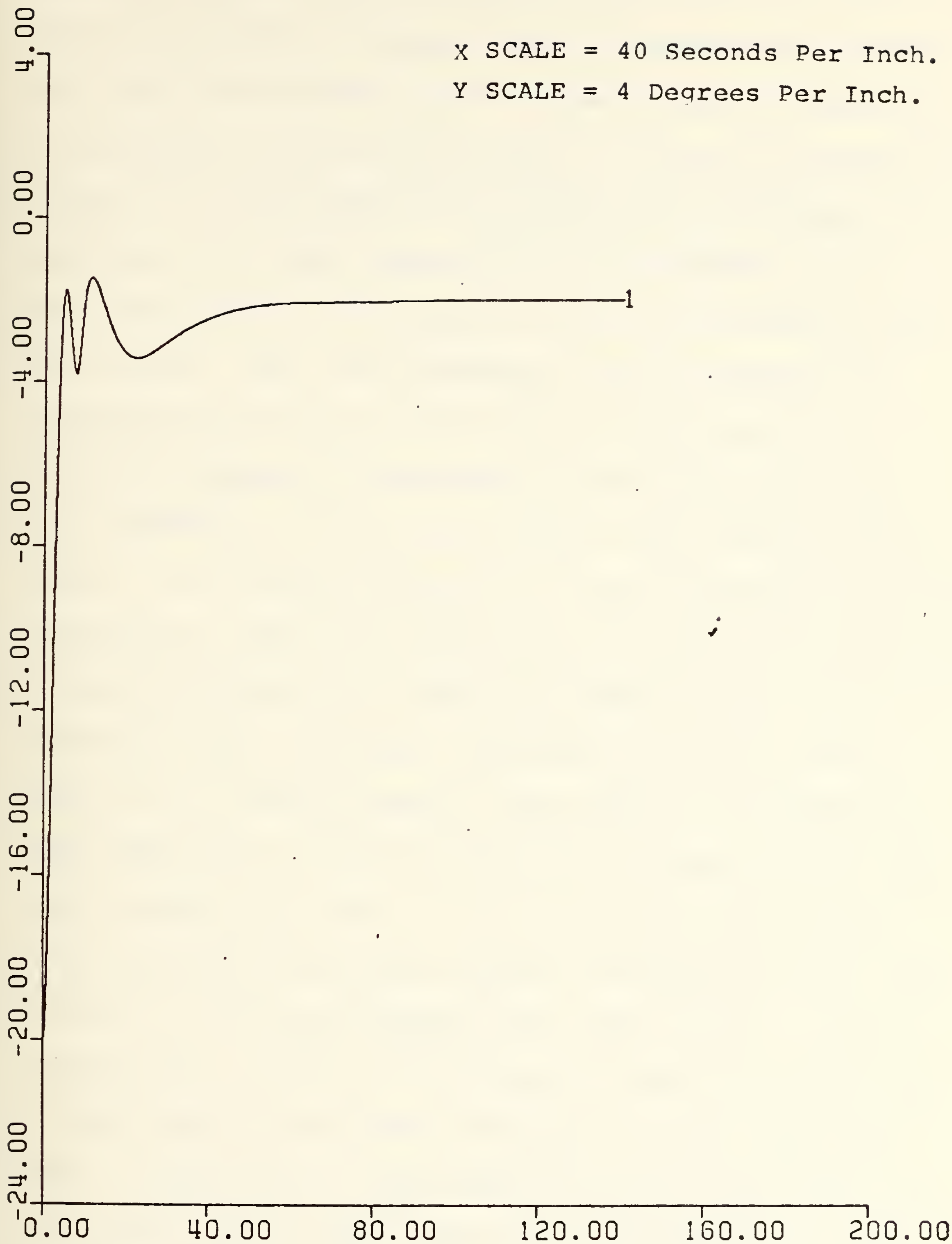


Figure 105. Roll vs. Time. Final Result With Roll Error Limiter. K1 = 3, K2 = 10. UCK = 12 Knots. Rudder Ordered = 35°. Initial Roll Angle = -20°.

same test without roll limiter as was discussed above gave an unstable system but after inserting the limiter the result was stable over the speed range of interest. In contrast to the results shown in Figures 67 through 71, there is no oscillation in the roll and sailplanes responses in the time interval of 0 - 20 seconds and it was observed that the limiter gave very good damping to the system. This last statement can be justified by inspection of Figure 75 such that at time equal 20 (when the rudder is commanded to full deflection) the roll response is almost zero without any previous oscillation. As the stabilization in three dimensions was being reached the stern and sailplanes never went into saturation.

2. Figures 88 through 102 record the depth, pitch, roll, sternplane and sailplanes responses at 24, 18, and 12 knots to 35° rudder command (the rudder is commanded to full deflection of the beginning of the simulation) with zero initial roll angle. It is observed that without using excessive stern and sailplane deflection great stability in the three dimension has been reached. As was shown before, Figures 44 through 55 record the responses of the system without roll controller to the identical test. Comparison of these tests is made in the Table II. It is seen that at high speed great improvement in the sense of maximum and steady state value has been obtained.

TABLE II

IMPROVEMENT DUE TO ROLL CONTROLLER

UCK		WITHOUT ROLL CONTROLLER		WITH ROLL CONTROLLER	
		MAX	STEADY STATE	MAX	STEADY STATE
24	Depth Changed			8.5 ft.	8 ft.
	Pitch		UNSTABLE	$5^{o}.5$	$4^{o}.4$
	Roll			$5^{o}.3$	4^{o}
18	Depth Changed	10.1	8.7	8.5	8 ft.
	Pitch	9.5	5^{o}	$5^{o}.6$	$4^{o}.7$
	Roll	23^{o}	6^{o}	$4^{o}.6$	$3^{o}.2$
12	Depth Changed	9.7 ft.	9.5 ft.	9.2	9
	Pitch	7^{o}	$5^{o}.7$	6.7	5.2
	Roll	$10^{o}.3$	2.5	$3^{o}.5$	2^{o}

3. Figures 103 through 105 record the roll responses of the system at 24, 18, and 12 knots to 35° rudder deflection (the turn was commanded at the beginning of the simulation) with 20° inboard roll angle. The results are stable. Comparison of Figure 103 with Figure 66 shows the improvement obtained by inserting a roll limiter such that it damped out the oscillation.

It was shown that utilizing the fairwater planes as the control surface of the roll controller not only stabilized the roll response but also gave big improvement in the depth and pitch controller. In the following section stability tests of the system to disturbance moments is discussed.

C. ROLL CONTROLLER STABILITY TESTS

Since the roll controller design was carried out using nonlinear equations in six degrees of freedom, the stability analysis of the system was not practical. To investigate the stability computer simulation was used by applying disturbance moments. The magnitude of the moments was

DISTURBANCE = $KS*(UCK)^{2}*L^{3}$ where

$KS = 4.0*0.0003*576/(UCK)^{2}$

The disturbance moment was calculated by assigning non-zero value of KS which was normally zero and represents the hydrodynamic coefficient which gives the rolling moment when body angle and control surface angles are zero. The magnitude of the disturbance was four times bigger than that used in the stability analysis of Stamps controller. At 24 knots the

magnitude of the disturbance was 1.1028×10^7 ft-lb. such that the Stamps controller was unable to stabilize the system to the disturbances of the magnitude in the order of 10^7. Figures 106 through 120 record the depth, pitch, roll, sternplane, and sailplanes responses to the inboard roll moment disturbance mentioned above. The distrubance was applied at time equal 20 as a step moment. Curve number 2 represents the disturbances. Inspection of the results shows that the system is stable in three dimensions to the disturbances moment. The worst affect of the disturbances was seen at low speed test which was normal. But even in this case, after a transient response the system was stable.

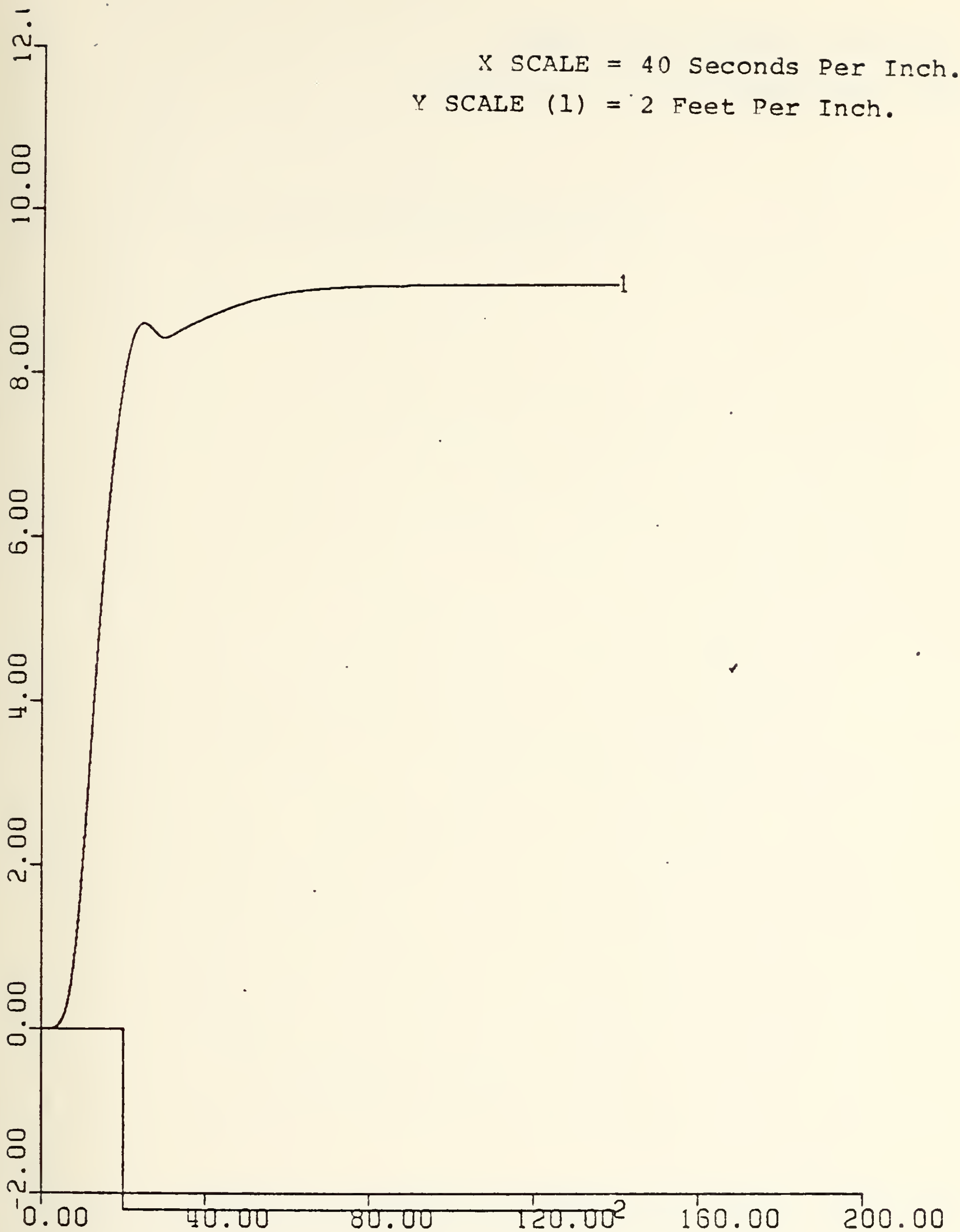


Figure 106.1. Depth vs. Time. Roll Stability Step Test.
UCK = 24 Knots. Rudder Ordered = 35°.
.2. Disturbance Moment vs. Time ($1.1028*10^7$ ft-lb.).

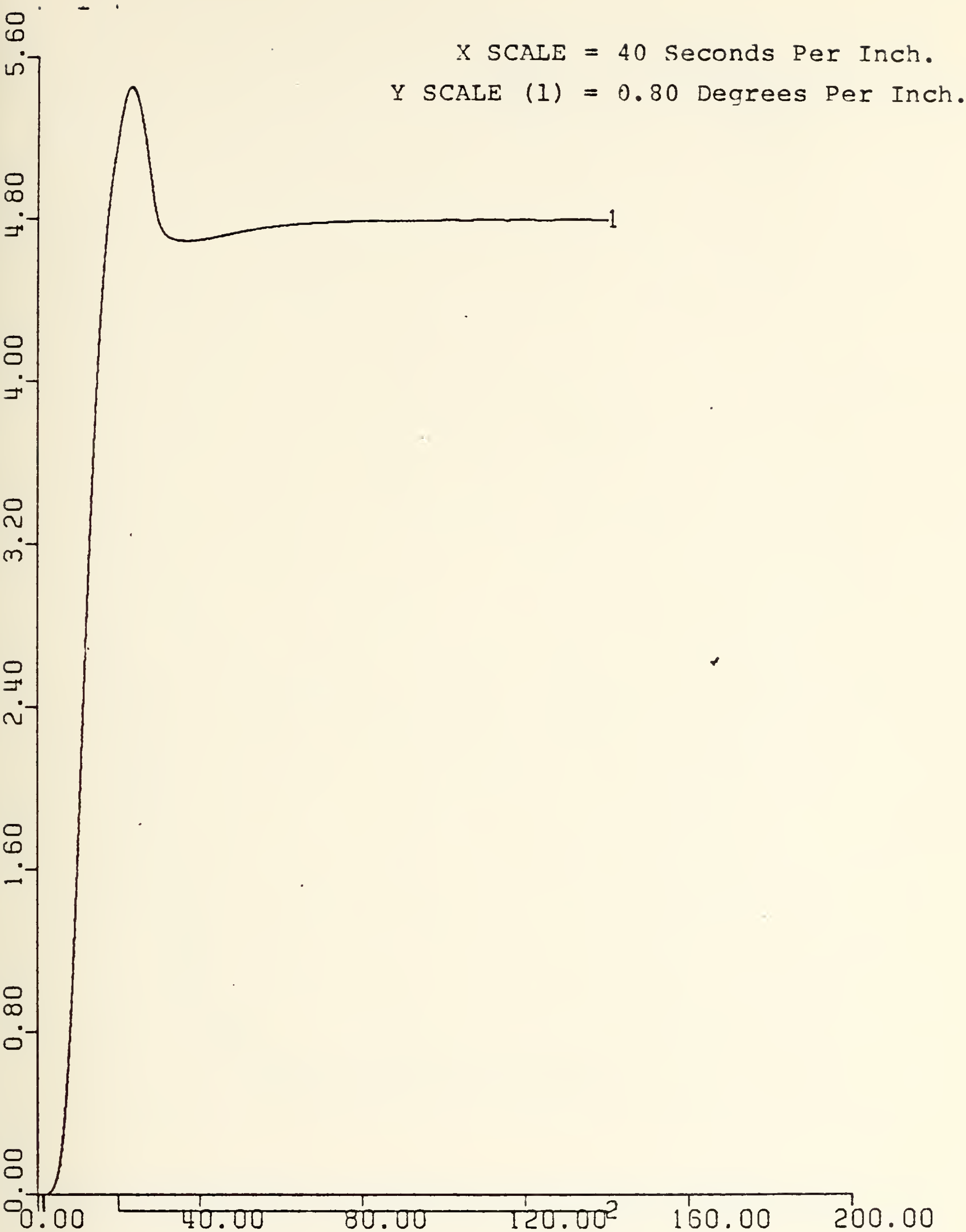


Figure 107.1. Pitch vs. Time. Roll Stability Step Test.
UCK = 24 Knots. Rudder Ordered = 35°.
.2. Disturbance vs. Time. ($1.1028*10^7$ ft-lb.).

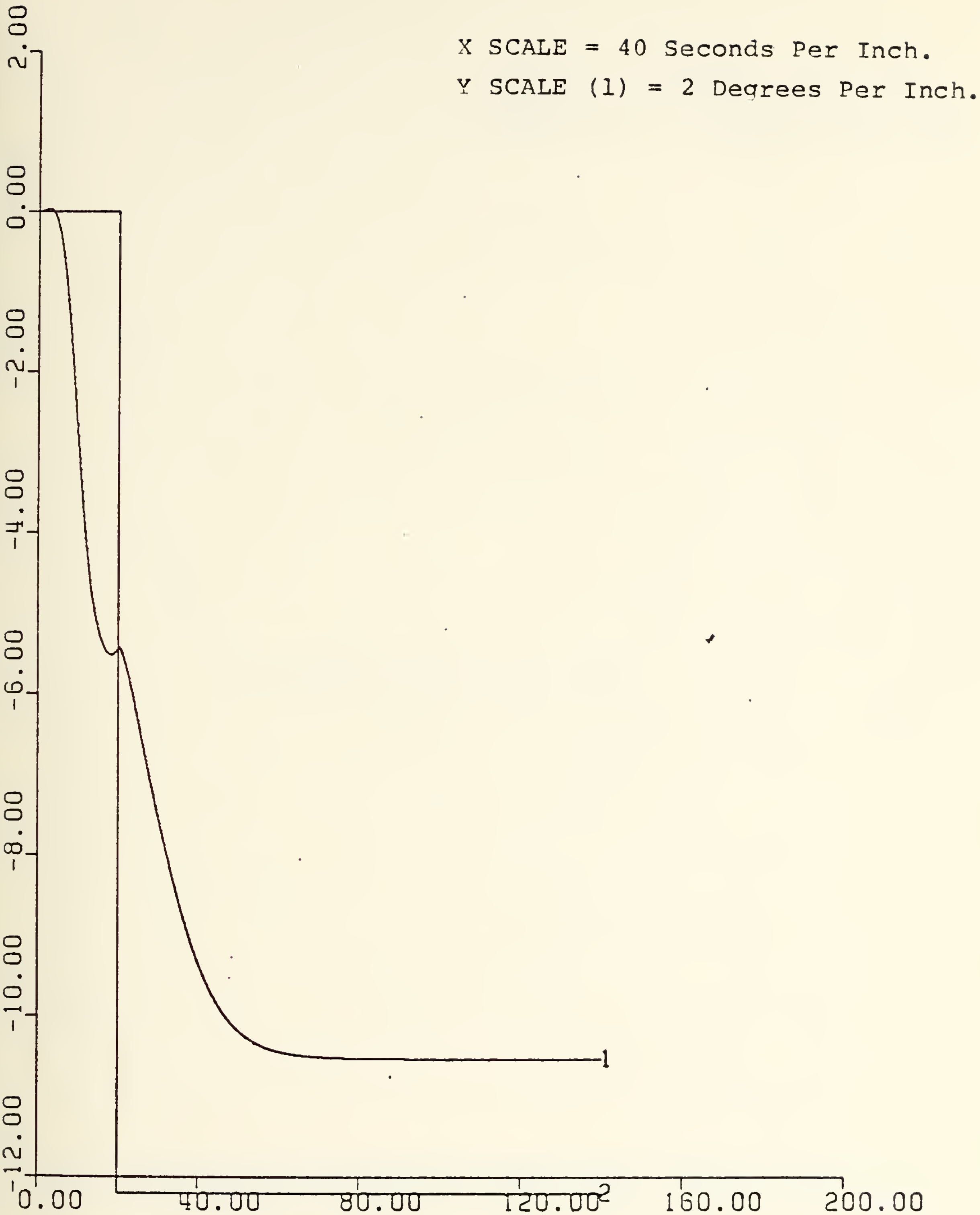


Figure 108.1. Roll vs. Time. Roll Stability Step Test. UCK = 24 Knots. Rudder Ordered = 35°.

.2. Disturbance Moment vs. Time (1.1028×10^7 ft-lb.).

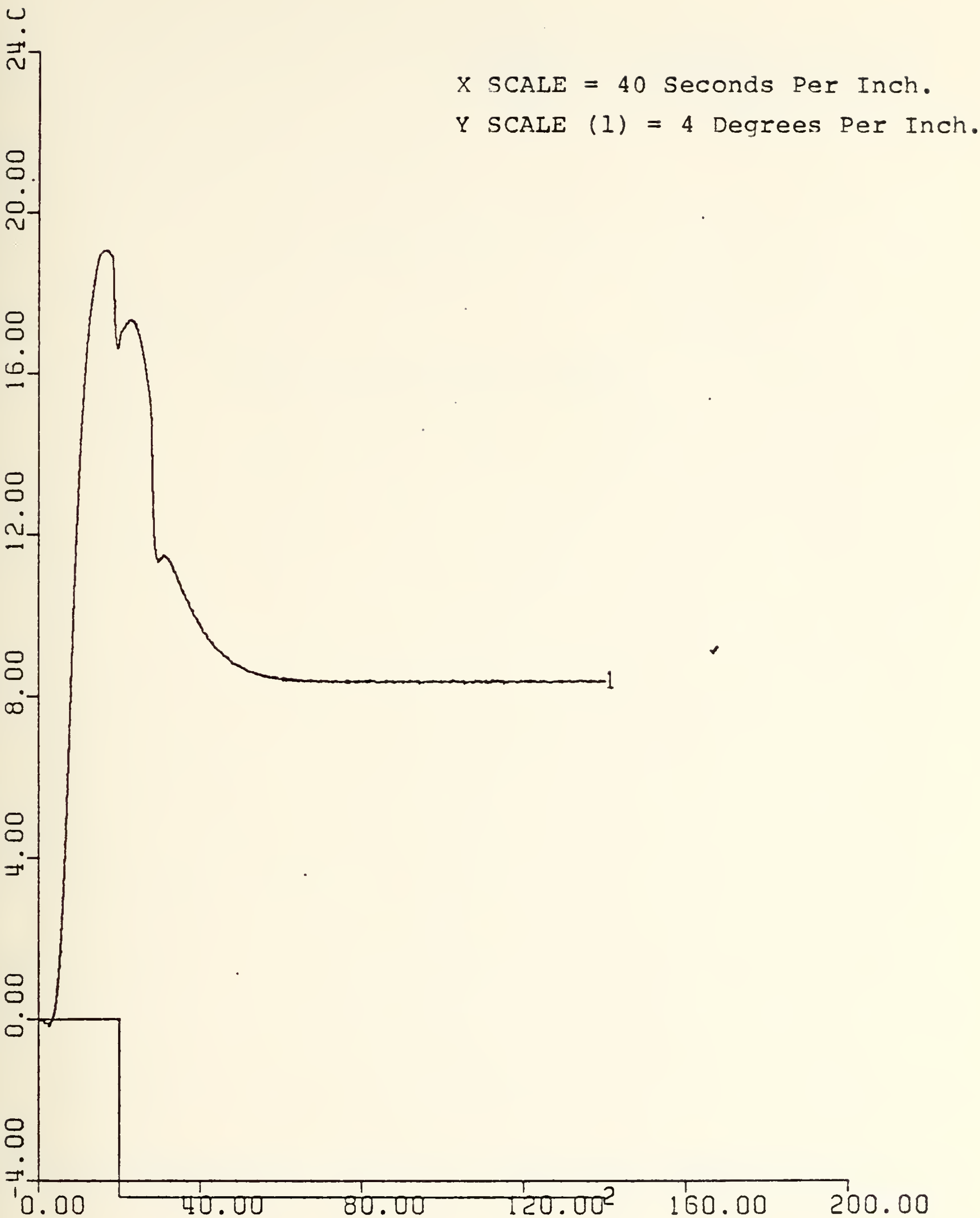


Figure 109.1. Sternplane Angle vs. Time. Roll Stability Step Test. UCK = 24 Knots. Rudder Ordered = 35°.
.2. Disturbance Moment vs. Time (1.1028×10^7 ft-lb.).

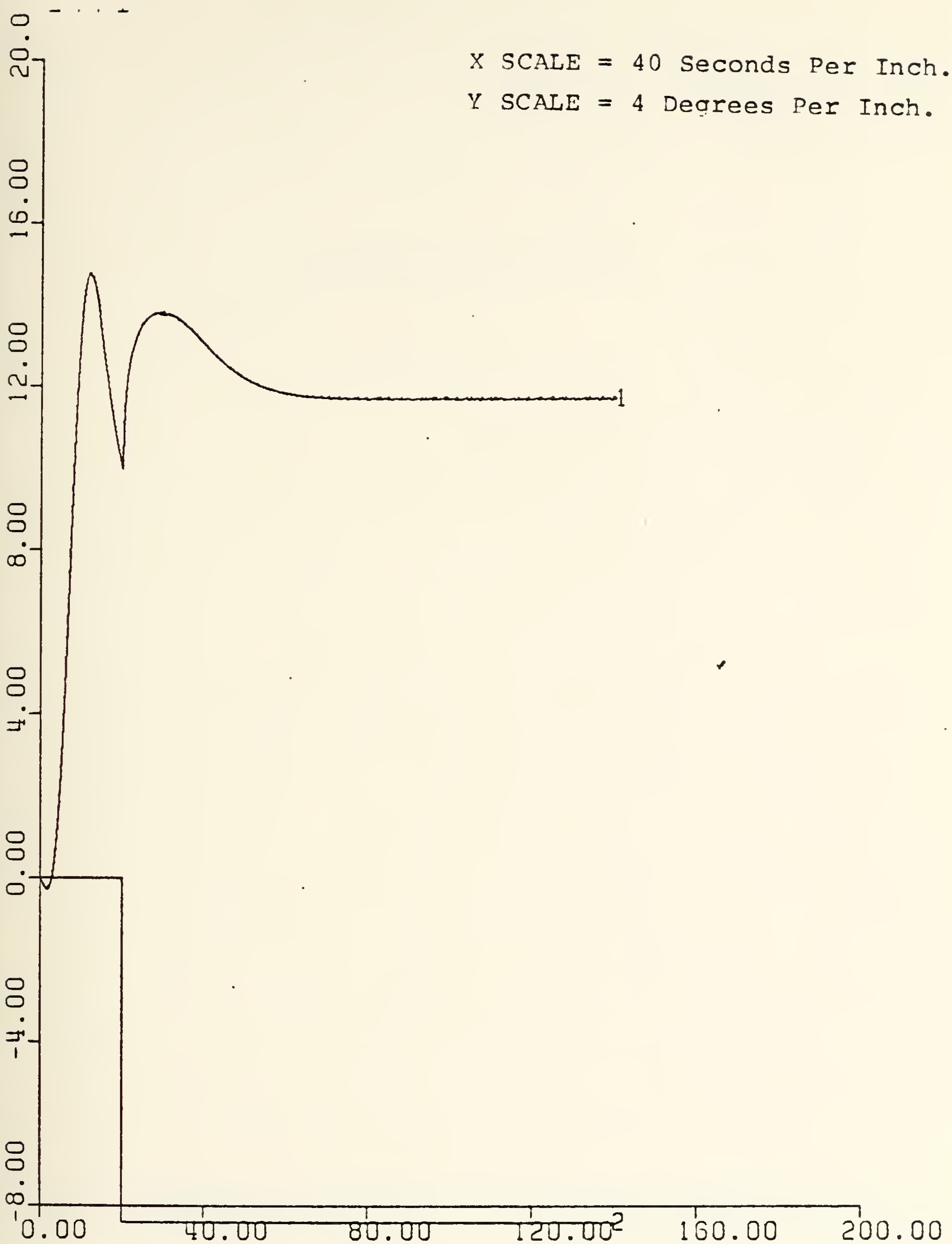


Figure 110.1. Sailplane Angle vs. Time. Roll Stability Step Test. UCK = 24 Knots. Rudder Ordered = 35°.

.2. Disturbance Moments vs. Time. (1.1028×10^{7} ft-lb.).

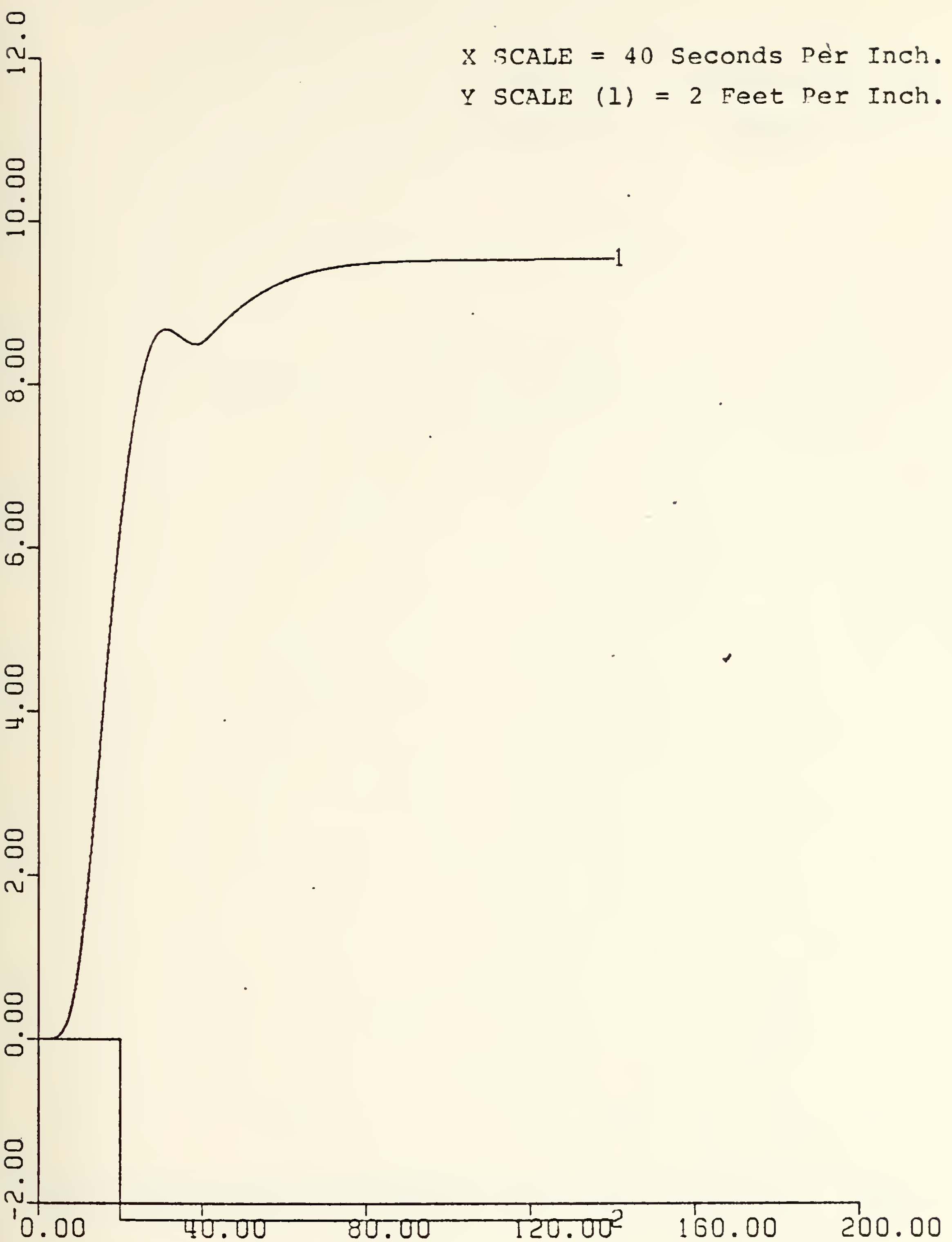


Figure 111.1. Depth vs. Time. Roll Stability Step Test.
UCK = 18 Knots. Rudder Ordered = 35°.
.2. Disturbance Moment vs. Time. (1.1028×10^{7} ft-lb.).

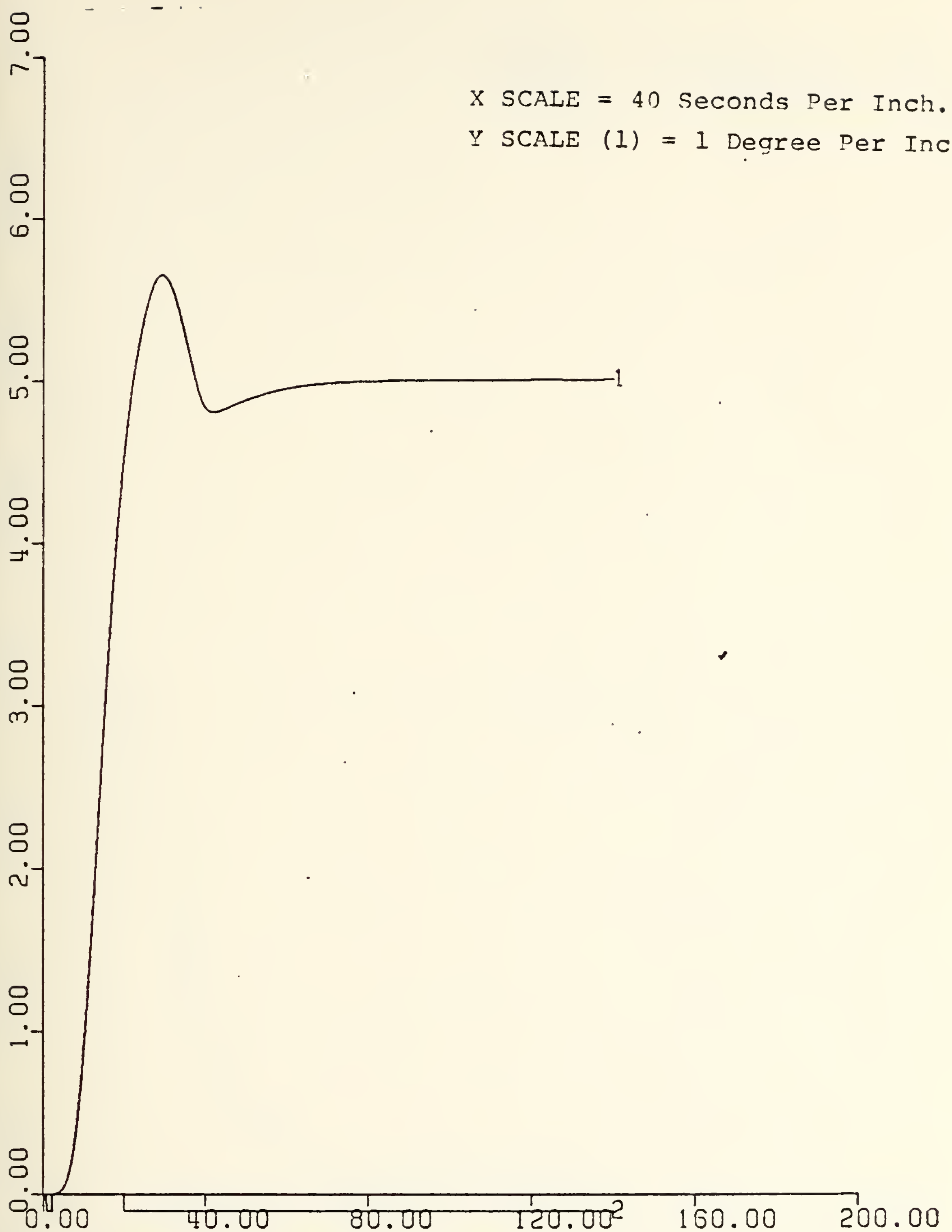


Figure 112.1. Pitch vs. Time. Roll Stability Step Test.
UCK = 18 Knots. Rudder Ordered = 35°.
.2. Disturbance Moment vs. Time. (1.1028×10^7 ft-lb.).

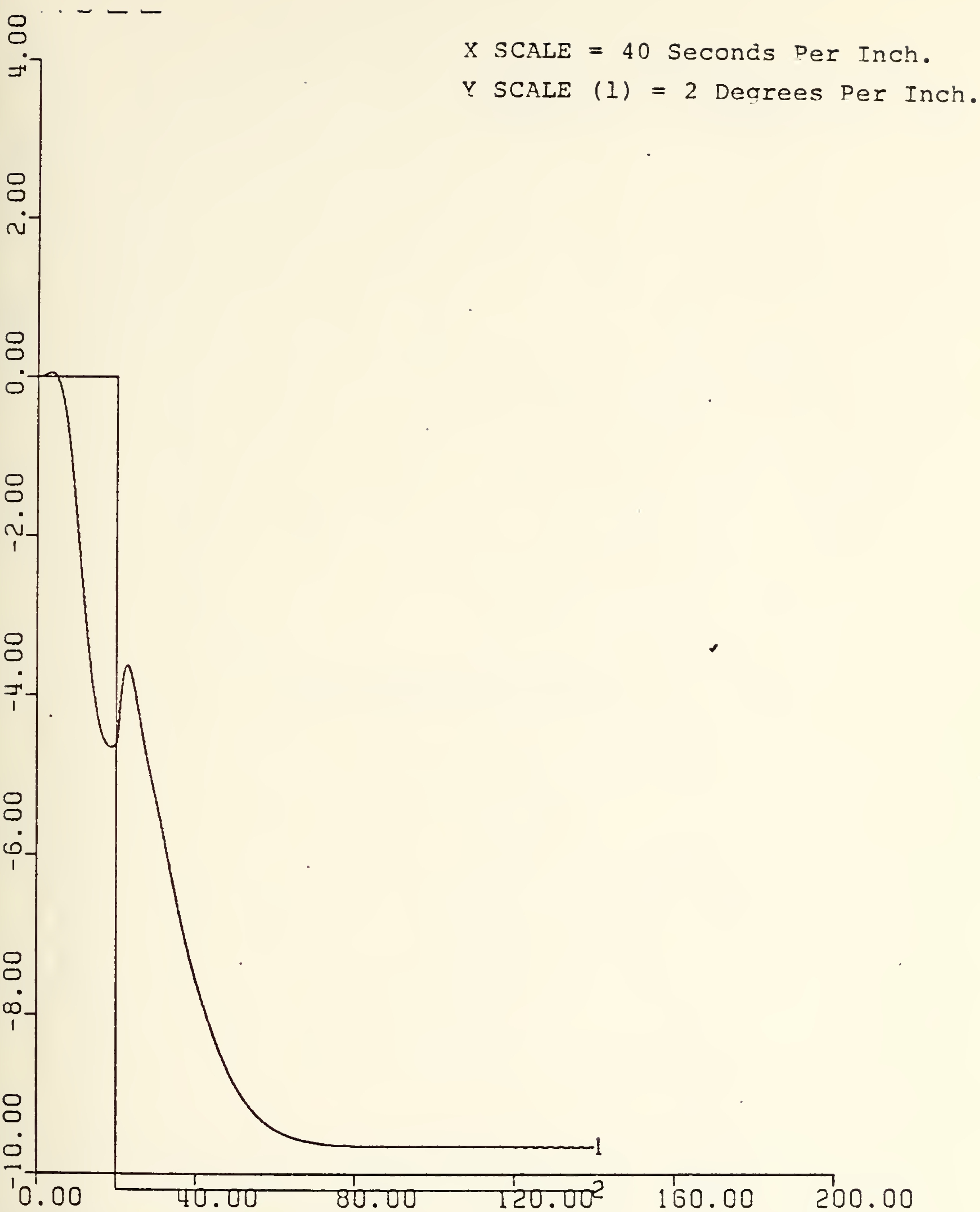


Figure 113.1. Roll vs. Time. Roll Stability Step Test. UCK = 18 Knots. Rudder Ordered = 35°.

.2. Disturbance Moment vs. Time. (1.1028×10^7 ft-lb.).

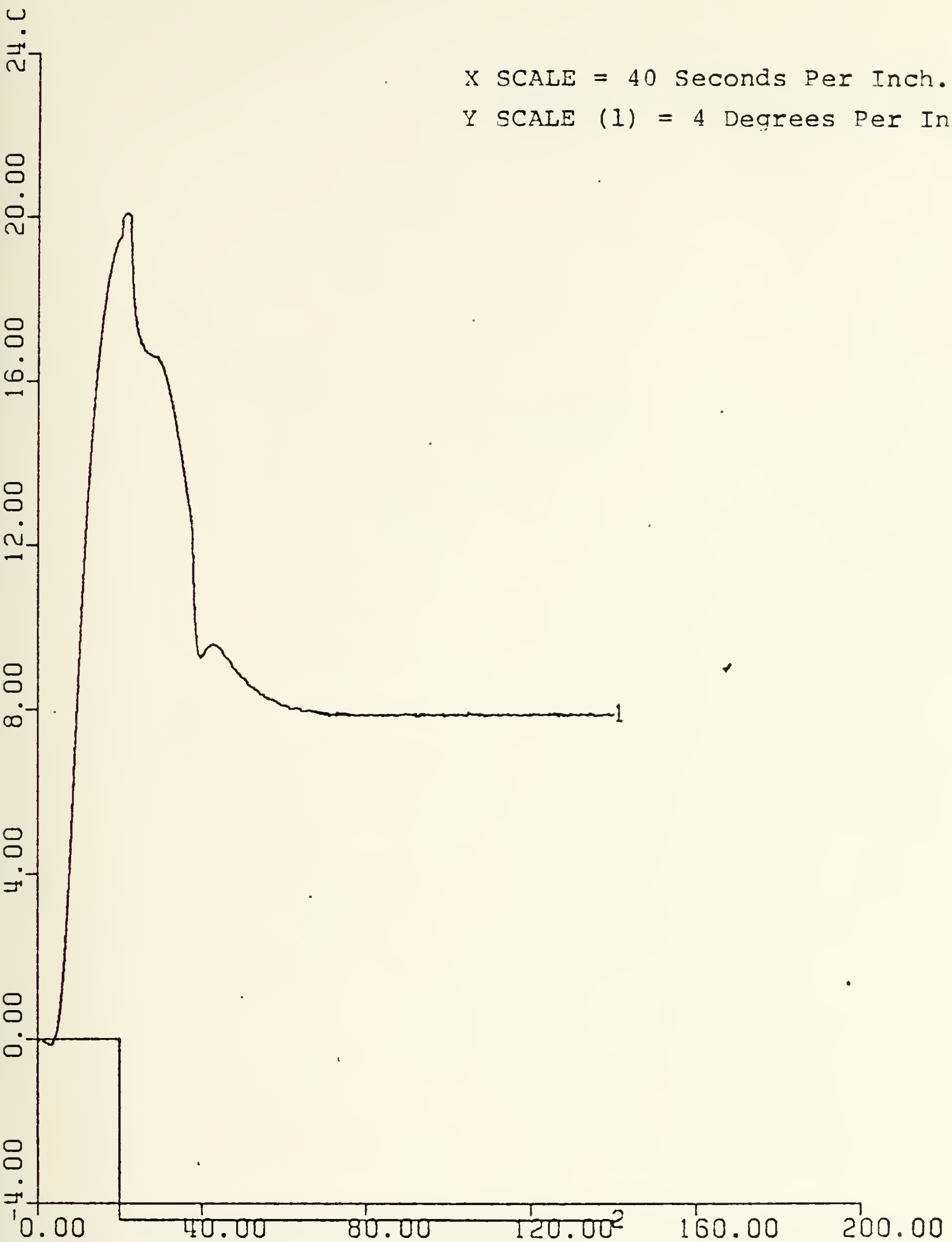


Figure 114.1. Sternplane Angle vs. Time. Roll Stability Step Test. UCK = 18 Knots. Rudder Ordered = 35^{o}.

.2. Disturbance Moment vs. Time. ($1.1028 x 10^{7}$ ft-lb.).

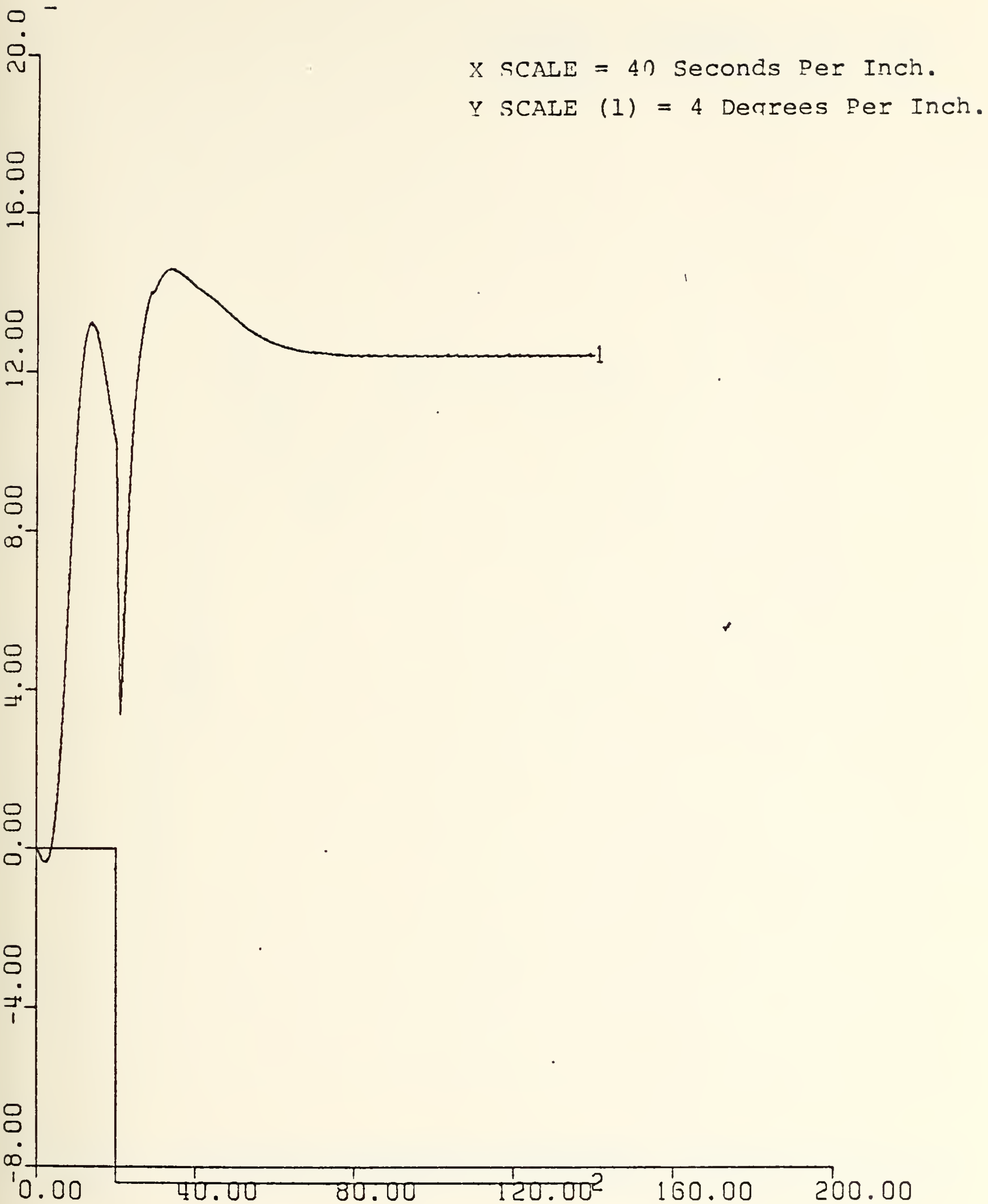


Figure 115.1. Sailplane Angle vs. Time. Roll Stability Step Test. UCK = 24 Knots. Rudder Ordered = 35°.

.2. Disturbance Moment vs. Time. (1.1028×10^7 ft-lb.).

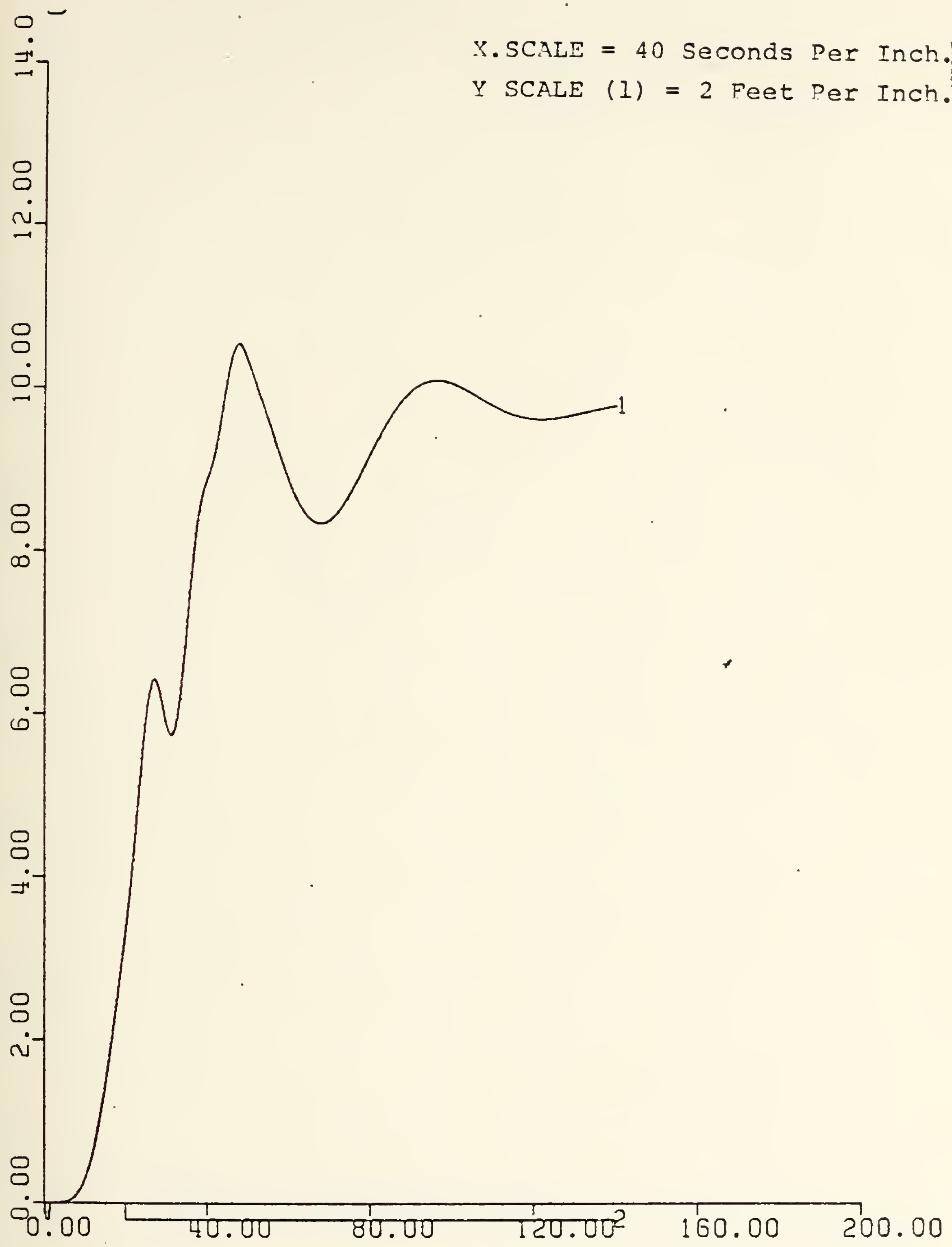


Figure 116.1. Depth vs. Time. Roll Stability Step Test.
UCK = 12 Knots. Rudder Ordered = 35^{o}.
.2. Disturbance Moment vs. Time. ($1.1028x10^{7}$ft-lb.).

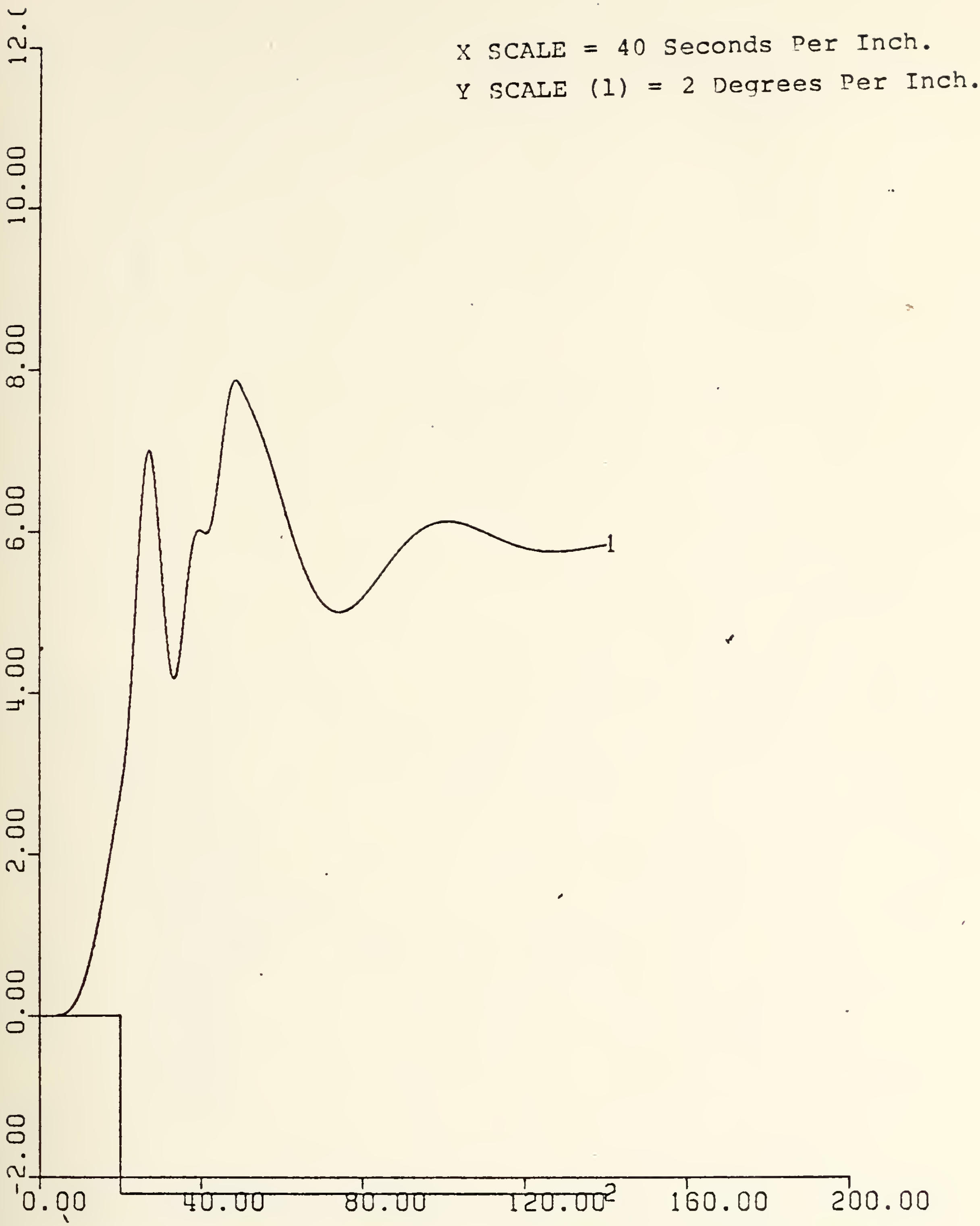


Figure 117.1. Pitch vs. Time. Roll Stability Step Test.
UCK = 12 Knots. Rudder Ordered = 35°.
.2. Disturbance Moment vs. Time. (1.1028×10^7 ft-lb.).

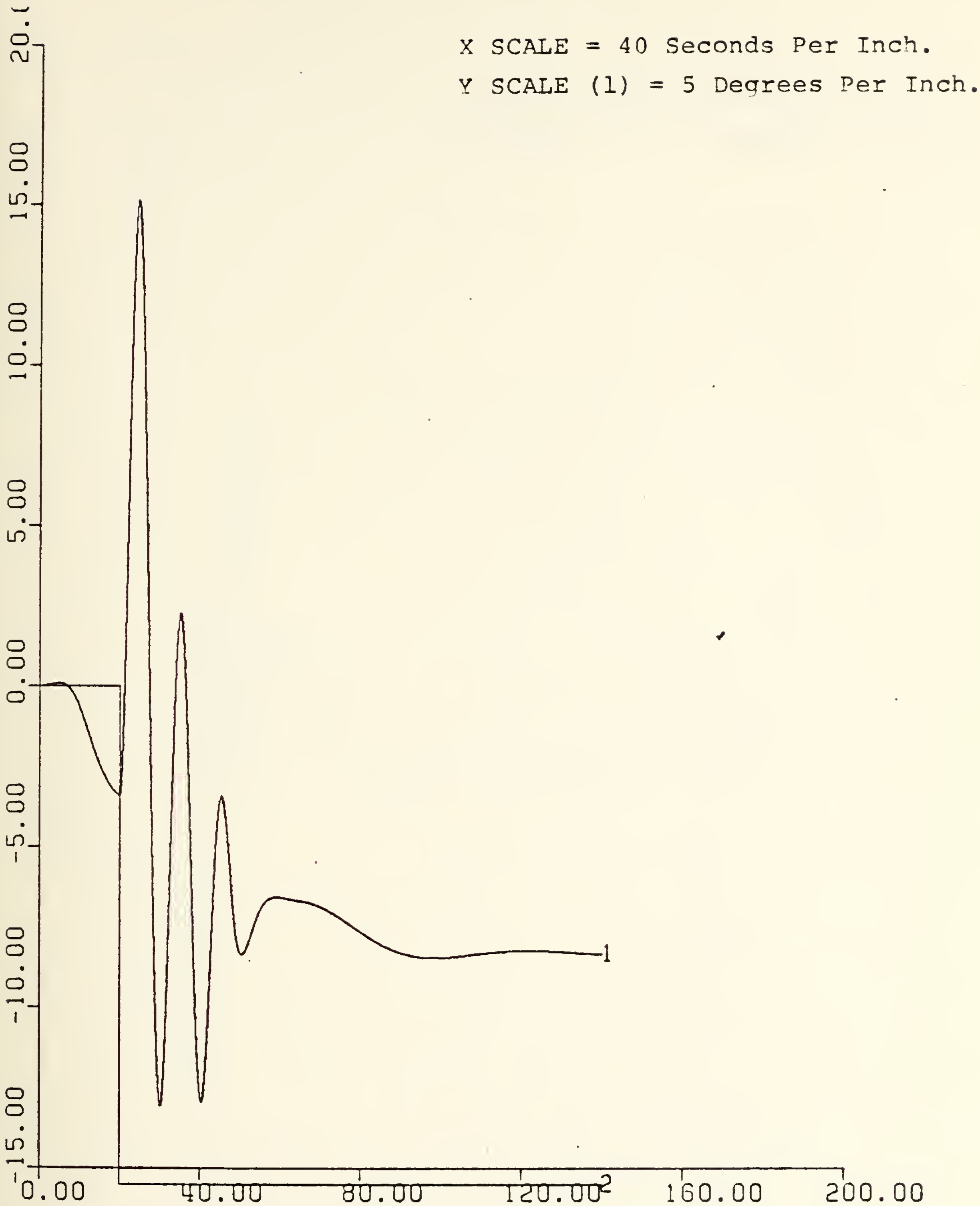


Figure 118.1. Roll vs. Time. Roll Stability Step Test. UCK = 12 Knots. Rudder Ordered = 35°.

.2. Disturbance Moment vs. Time. (1.1028×10^{7} ft-lb.).

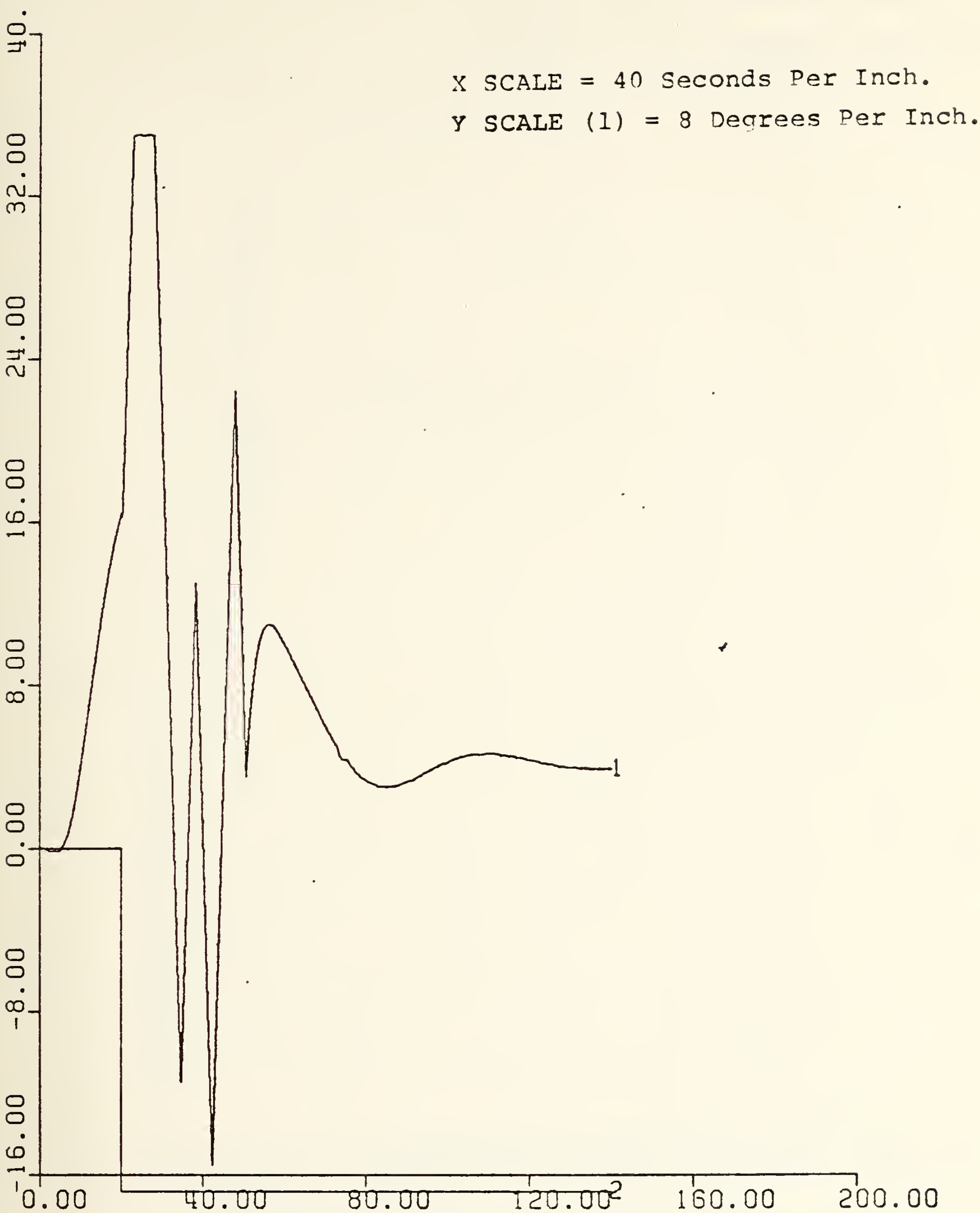


Figure 119.1. Sternplane Angle vs. Time. Roll Stability Step Test. UCK = 6 Knots. Rudder Ordered = 35°.

.2. Disturbance Moment vs. Time. (1.1028×10^7 ft-lb.).

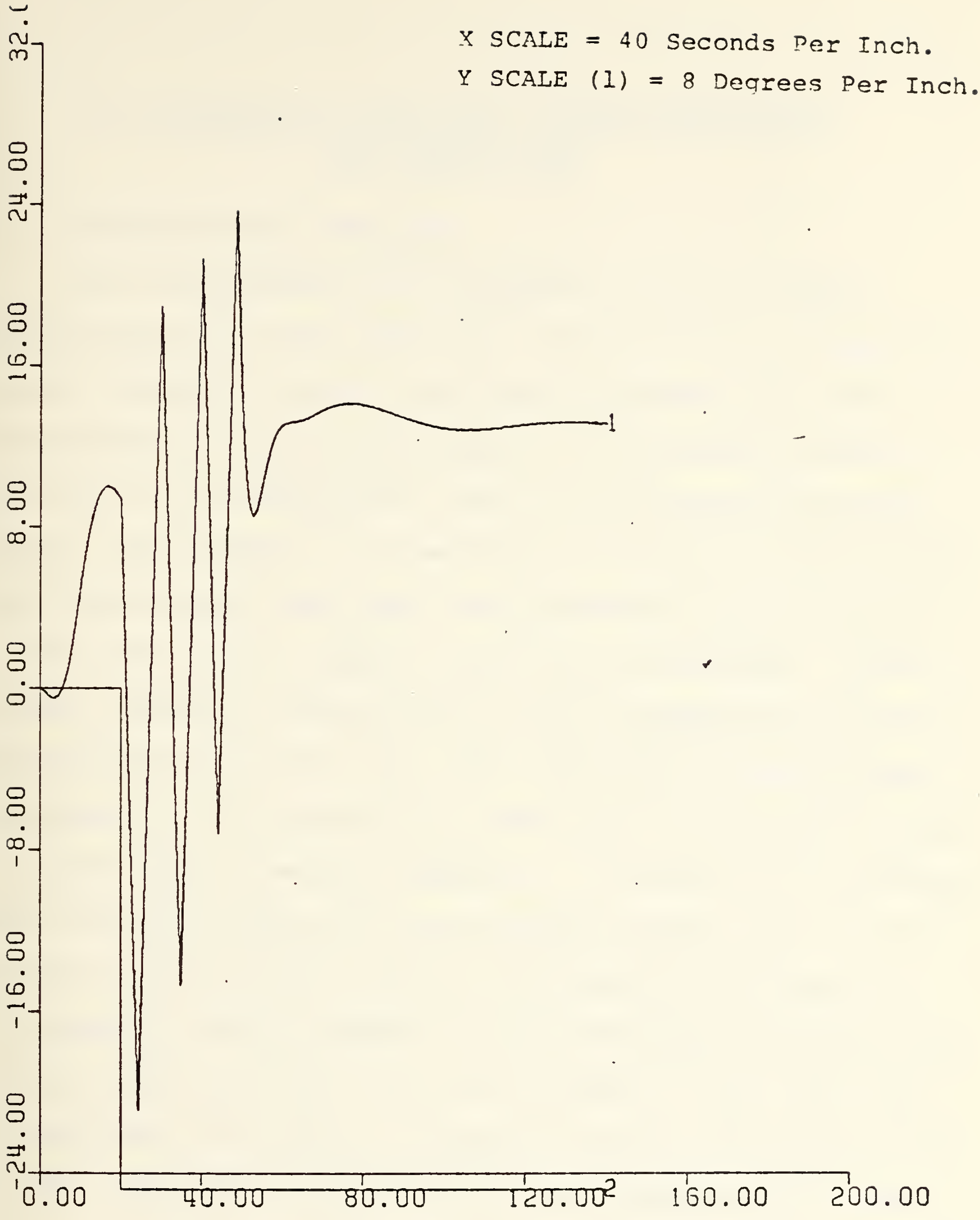


Figure 120.1. Sailplane Angle vs. Time. Roll Stability Step Test. UCK = 12 Knots. Rudder Ordered = 35°.
.2. Disturbance Moment vs. Time. (1.1028×10^7 ft-lb.).

VI. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

A. DISCUSSION AND CONCLUSION

The characteristic of a submarine which is totally submerged and in a high speed turn was discussed in Chapter II and the simulation results were given in Chapter III. The unhydrodynamic body structure when it is submerged, which is mainly due to the appendages (sail), was considered the main source of the problem. The necessity of the sail that provides rooms for periscope and other vital controls that are located in the tower does not permit a small sail structure. On this account, a control scheme must be used to compensate the problems that stem from the sail. The complexity of controlling a submarine in a high speed turn, comes from the coupling between states and three-dimension dynamics. In Chapter IV an automatic depth and pitch controller was presented briefly with the modification of the original design represented in Reference 7. The automatic control scheme gave the advantage of taking depth and pitch error and their rate into account. But, since only the sternplane was used as a control surface, the results made the roll controller design necessary for controlling the ship within the wide range of speeds and under various disturbance conditions. The imposition of the fairwater plane to control roll, which was the main goal of this thesis, gave a great amount of expected improvement to the system. The roll

controller scheme was carried out by using equations of motion (nonlinear) in which the vertical plane dynamics were stabilized by the imposition of the depth-pitch controller, and roll state and roll rate gave enough information to provide closed-loop control for the ship. The control scheme was a direct roll controller compared to the controller designed by Stamps in Reference 2. Stamps's controller was an indirect roll controller and in his design the rudder was used as a function of the integral of roll error which was the difference between the allowed maximum roll and the actual instantaneous roll angles. The initial rudder ordered was to be such that the peak roll expected for a given approach speed would be less than the maximum allowed roll. The integral of roll error was then to be computed and scaled to represent an additive tern applied to the initial rudder order (δro). The instantaneous rudder order (DRCOM) was then to be computed

$$DRCOM = \delta ro + K_I \, (\phi_{max} - \phi_{act}) \; dt.$$

The technique reported in this thesis has the benefits of simplicity and costs much less than alterations of the design criteria of Navy submarines. But since it prohibited use of a hard rudder deflection (35^o) in the early phase of turn, the time required to pass any specified yaw angle was quite long. For this reason, the roll control, in a direct sense, by making use of fairwater planes as control fins, was investigated in the proposed design. As a result, not only were the dangerous snap rolls decreased to magnitudes of 5^o, but also with the hard

rudder deflection a big yaw rate was achieved. In Table III, the performance of the submarine with each of these two roll controllers is compared. In the Stamps' design, maximum roll angle is predetermined and the controller is designed not to exceed this value. The higher allowed maximum roll angle gives higher yaw rates. In the proposed design, maximum roll angle is the result of the system's dynamics.

TABLE III

COMPARISON OF THE PROPOSED AND STAMPS'DESIGN

TYPE OF CONTROLLER	MAX ROLL	APPROACH SPEED	TIME REQUIRED IN SECONDS TO PASS SPECIFIED YAW ANGLE		
			45°	90°	180°
STAMPS'DESIGN	$7^\circ.5$	24	52	91	7100
		18	39	67	7100
		12	27	47	83
DIFFERENTIAL FAIRWATER PLANE	$5^\circ.61$	24	11.5	20	41
	$4^\circ.69$	18	14	25	54
	$3^\circ.4$	12	19	36	80

It is seen that the use of differential fairwater planes provides a faster response with reduced maximum roll angle at all speeds.

In the proposed design, only one fairwater plane actuator was used and it was assumed that it gives deflection in a differential mode. Switching criteria from the conventional usage of the fairwater plane (both starboard and port sides move simultaneously in the same direction) to the differential mode was not discussed.

This research has shown that imposition of the fairwater plane as a part of the roll controller improved the control of a turning high speed submarine in three dimensions. Dangerous snap roll was decreased to around 5° and with only sternplane and the stabilized roll response high improvement in the depth and pitch characteristic was achieved.

B. RECOMMENDATIONS FOR FURTHER WORK

The following research would be worthwhile in future studies:

1. Automatic depth and pitch controller by using only sternplane in the sense of an optimal feedback controller for linear tracking should be designed and the combination of this design with the present roll controller should be investigated. This study would give good insight into the problem which comes from the depth changing when the submarine is in a high speed turn.
2. Switching criteria from the roll controller of Reference 2 to the proposed roll controller should be established and these two designs should combine together. This would give better depth and pitch control to the ship when it has low speed where a great amount of roll control is not needed.
3. With the coordination of NSRDC a more accurate hydrodynamic coefficient associated with the differentially deflected sailplane should be obtained.

4. Addition of an integral of error to the roll control should be studied to see if the steady state roll angle can be reduced.

APPENDIX A

EQUATIONS OF MOTION

The following set of equations are referred to a body fixed system of axes which are coincident with the principal axes of inertia of the body. The origin of this axis-system is located at the assumed center of mass of the body

Equation of Motion Along the Body Axis System x-Axis

$$m(\dot{u} - vr + wq) = \frac{\rho}{2} \ell^4 \left[X_{qq}' q^2 + X_{rr}' r^2 + X_{rp}' rp\right]$$

$$+ \frac{\rho}{2} \ell^3 \left[X_{\dot{u}}' \dot{u} + X_{vr}' vr + X_{wq}' wq\right]$$

$$+ \frac{\rho}{2} \ell^2 \left[X_{uu}' u^2 + X_{vv}' v^2 + X_{ww}' w^2\right]$$

$$+ \frac{\rho}{2} \ell^2 u^2 \left[X_{\delta r \delta r}' \delta_r^{\,2} + X_{\delta s \delta s}' \delta_s^{\,2} + X_{\delta b \delta b}' \delta_b^{\,2}\right]$$

$$+ \frac{\rho}{2} \ell^2 X_{vvn'}' (n' - 1) v^2$$

$$+ \frac{\rho}{2} \ell^2 X_{wwn'}' (n' - 1) w^2$$

$$+ \frac{\rho}{2} \ell^2 u^2 X_{\delta s \delta s n'}' (n' - 1) \delta_s^{\,2}$$

$$+ \frac{\rho}{2} \ell^2 u^2 X_{\delta r \delta r n'}' (n' - 1) \delta_r^{\,2}$$

$$- \Sigma W_i \sin \theta$$

$$+ (F_x)_P$$

Equation of Motion Along the Body Axis System y-Axis

$$m(\dot{v} - wp + ur) = \frac{\rho}{2} \ell^4 \left[Y_{\dot{r}}' \dot{r} + Y_{\dot{p}}' \dot{p} \right]$$

$$+ \frac{\rho}{2} \ell^4 \left[Y_{pq}' pq + Y_{p|p|}' p|p| \right]$$

$$+ \frac{\rho}{2} \ell^3 \left[Y_{\dot{v}}' \dot{v} + Y_{wp}' wp + Y_{v|r|}' \frac{v}{|v|} \left|(v^2 + w^2)^{\frac{1}{2}}\right| |r| \right]$$

$$+ \frac{\rho}{2} \ell^3 \left[Y_r' ur + Y_{|r|\delta r}' u|r|\delta r + Y_p' up \right]$$

$$+ \frac{\rho}{2} \ell^3 \; Y_{rn'}' (n' - 1) ur$$

$$+ \frac{\rho}{2} \ell^2 \left[Y_*' u^2 + Y_v' uv + Y_{v|v|}' v\left|(v^2 + w^2)^{\frac{1}{2}}\right| \right]$$

$$+ \frac{\rho}{2} \ell^2 u^2 Y_{\delta r}' \delta_r$$

$$+ \frac{\rho}{2} \ell^2 u^2 Y_{\delta r n'}' (n' - 1) \delta_r$$

$$+ \frac{\rho}{2} \ell^2 Y_{vn'}' (n' - 1) uv$$

$$+ \frac{\rho}{2} \ell^2 Y_{v|v|n'}' (n' - 1) v\left|(v^2 + w^2)^{\frac{1}{2}}\right|$$

$$+ \frac{\rho}{2} \ell^2 \; Y_{wv}' wv\#$$

$$+ \frac{\rho}{2} \ell^2 (F_y)_{vs} \; \frac{v^2 + w^2}{U} \; (-w) \; \text{Sin}\, \omega t$$

$$+ \Sigma W_i \sin\phi \cos\theta$$

\# Multiplied by $\frac{u}{U}$ for large angles of attack near -90°

Equation of Motion Along the Body Axis System z-Axis

$$m(\dot{w} - uq + vp) = \frac{\rho}{2} \ell^4 Z_{\dot{q}}' \dot{q}$$

$$+ \frac{\rho}{2} \ell^4 \left[Z_{rr}' r^2 \# + Z_{rp}' rp \# \right]$$

Note 1

$$+ \frac{\rho}{2} \ell^3 \left[Z_{\dot{w}}' \dot{w} + Z_{vr}' vr \# + Z_{vp}' vp + \Delta Z_{vp}' vp \# \right]$$

$$+ \frac{\rho}{2} \ell^3 \left[Z_q' uq + Z_{|q|\delta s}' u|q|\delta s + Z_{w|q|}' \frac{w}{|w|} |(v^2 + w^2)^{\frac{1}{2}}| \, |q| \right]$$

$$+ \frac{\rho}{2} \ell^3 \; Z_{qn'}' (n' - 1) uq$$

$$+ \frac{\rho}{2} \ell^2 \left[Z_*' u^2 + Z_w' uw + Z_{w|w|}' w |(v^2 + w^2)^{\frac{1}{2}}| \right]$$

$$+ \frac{\rho}{2} \ell^2 \left[Z_{|w|}' u|w| + Z_{ww}' |w (v^2 + w^2)^{\frac{1}{2}}| + Z_{vv}' v^2 \# \right]$$

$$+ \frac{\rho}{2} \ell^2 u^2 \left[Z_{\delta s}' \delta s + Z_{\delta b}' \delta b \right]$$

$$+ \frac{\rho}{2} \ell^2 \left[Z_{wn'}' (n' - 1) uw + Z_{w|w|n'}' (n' - 1) w |(v^2 + w^2)^{\frac{1}{2}}| \right]$$

$$+ \frac{\rho}{2} \ell^2 u^2 Z_{\delta s n'}' (n' - 1) \delta_s$$

$$+ \frac{\rho}{2} \ell^2 (F_z)_{vs} \frac{v^2 + w^2}{U} \; v \sin \omega t$$

$$+ \Sigma W_i \cos\theta \cos\phi$$

\# Multiplied by $\frac{u}{U}$ for large angles of attack near -90°

Note 1
when not multiplied by $\frac{u}{U}$ add to Z_{vp}'

Equation of Motion About the Body Axis System x-Axis

$$I_x\dot{p} + (I_z - I_y)\,qr = \frac{\rho}{2}\ell^5\left[K_{\dot{p}}'\,\dot{p} + K_{qr}'\,qr + K_{\dot{r}}'\,\dot{r} + K_{p|p|}'\,p|p|\right]$$

$$+ \frac{\rho}{2}\ell^4\left[K_p'\,up + K_r'\,ur + K_{\dot{v}}'\,\dot{v} + K_{wp}'\,wp\right]$$

$$+ \frac{\rho}{2}\ell^3\left[K_*'\,u^2 + K_v'\,uv + K_{v|v|}'\,v\left|(v^2 + w^2)^{\frac{1}{2}}\right|\right]$$

$$+ \frac{\rho}{2}\ell^3\,K_{vw}'\,vw$$

$$+ \frac{\rho}{2}\ell^3\,u^2K_{\delta r}'\,\delta_r$$

$$+ Bz_B\,\sin\phi\,\cos\theta$$

Equation of Motion About the Body Axis System y-Axis

Note 1

$$I_y\dot{q} + (I_x - I_z)\,rp = \frac{\rho}{2}\ell^5\left[M_{\dot{q}}{}'\,\dot{q} + M_{rr}{}'\,r^2\# + M_{rp}{}'\,rp + \Delta M_{rp}{}'\,rp\#\right]$$

$$+ \frac{\rho}{2}\ell^4\left[M_q{}'\,uq + M_{|q|\delta s}{}'\,u|q|\delta s + M_{|w|q}{}'\,|(v^2 + w^2)^{\frac{1}{2}}|q\right]$$

$$+ \frac{\rho}{2}\ell^4\left[M_{\dot{w}}{}'\,\dot{w} + M_{vr}{}'\,vr\# + M_{vp}{}'\,vp\#\right]$$

$$+ \frac{\rho}{2}\ell^4 M_{qn'}{}'\,(n' - 1)\,uq$$

$$+ \frac{\rho}{2}\ell^3\left[M_*{}'\,u^2 + M_w{}'\,uw + M_{w|w|}{}'\,w|(v^2 + w^2)^{\frac{1}{2}}|\right]$$

$$+ \frac{\rho}{2}\ell^3\left[M_{|w|}{}'\,u|w| + M_{ww}{}'\,|w\,(v^2 + w^2)^{\frac{1}{2}}| + M_{vv}{}'\,v^2\#\right]$$

$$+ \frac{\rho}{2}\ell^3\,u^2\left[M_{\delta s}{}'\,\delta_s + M_{\delta b}{}'\,\delta_b\right]$$

$$+ \frac{\rho}{2}\ell^3 M_{wn'}{}'\,(n' - 1)\,uw$$

$$+ \frac{\rho}{2}\ell^3 M_{w|w|n'}{}'\,(n' - 1)\,w|(v^2 + w^2)^{\frac{1}{2}}|$$

$$+ \frac{\rho}{2}\ell^3\,u^2 M_{\delta sn'}{}'\,(n' - 1)\,\delta_s$$

$$+ Bz_B \sin\theta$$

$$- \Sigma W_i\, x_{ti} \cos\theta\cos\phi$$

\# Multiply by $\frac{u}{U}$ for large angles of attack near -90°

Note 1
when not multiplied by $\frac{u}{U}$ add to $M_{rp}{}'$

Equation of Motion About the Body Axis System z-Axis

$$I_z\dot{r} + (I_y - I_x)\,pq = \frac{\rho}{2}\ell^5 \left[N_{\dot{r}}{}'\,\dot{r} + N_{pq}{}'\,pq + N_{\dot{p}}{}'\,\dot{p}\right]$$

$$+ \frac{\rho}{2}\ell^4 \left[N_r{}'\,ur + N_{|r|\delta r}{}'\,u|r|\delta r + N_{|v|r}{}'\,\left|(v^2 + w^2)^{\frac{1}{2}}\right| r\right]$$

$$+ \frac{\rho}{2}\ell^4 \left[N_p{}'\,up + N_{\dot{v}}{}'\,\dot{v} + N_{wp}{}'\,wp\right]$$

$$+ \frac{\rho}{2}\ell^4\ N_{rn'}{}'\,(n' - 1)\,ur$$

$$+ \frac{\rho}{2}\ell^3 \left[N_*{}'\,u^2 + N_v{}'\,uv + N_{v|v|}{}'\,v\left|(v^2 + w^2)^{\frac{1}{2}}\right|\right]$$

$$+ \frac{\rho}{2}\ell^3\ u^2 N_{\delta r}{}'\,\delta_r$$

$$+ \frac{\rho}{2}\ell^3\ u^2 N_{\delta rn'}{}'\,(n' - 1)\,\delta_r$$

$$+ \frac{\rho}{2}\ell^3\ N_{vn'}{}'\,(n' - 1)\,uv$$

$$+ \frac{\rho}{2}\ell^3\ N_{v|v|n'}{}'\,(n' - 1)\,v\left|(v^2 + w^2)^{\frac{1}{2}}\right|$$

$$+ \frac{\rho}{2}\ell^3\ N_{wv}{}'\ wv\#$$

$$+ \Sigma W_i\, x_{ti} \cos\theta \sin\phi$$

\# Multiply by $\frac{u}{U}$ for large angles of attack near -90°

AUXILIARY EQUATIONS

$$\dot{\phi} = p + \dot{\psi}\sin\theta$$

$$\dot{\theta} = (q - \dot{\psi}\cos\theta\sin\phi)/\cos\phi$$

$$\dot{\psi} = (r + \dot{\theta}\sin\phi)/\cos\theta\cos\phi$$

$$\dot{x}_o = u\cos\theta\cos\psi + v(\sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi) + w(\sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi)$$

$$\dot{y}_o = u\cos\theta\sin\psi + v(\cos\phi\cos\psi + \sin\phi\sin\theta\sin\psi) + w(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)$$

$$\dot{z}_o = -u\sin\theta + v\cos\theta\sin\phi + w\cos\theta\cos\phi$$

$$U = (u^2 + v^2 + w^2)^{\frac{1}{2}}$$

$$(F_x)_P = \frac{\rho}{2}\ell^2 u^2\left[a_1' + a_2' n' + a_3' n'^2\right] \quad \text{when } k_1 < n'$$

$$= \frac{\rho}{2}\ell^2 u^2\left[b_1' + b_2' n' + b_3' n'^2\right] \quad \text{when } k_2 < n' < k_1$$

$$= \frac{\rho}{2}\ell^2 u^2\left[c_1' + c_2' n' + c_3' n'^2\right] \quad \text{when } k_3 < n' < k_2$$

$$= \frac{\rho}{2}\ell^2 u^2\left[d_1' + d_2' n' + d_3' n'^2\right] \quad \text{when } n' < k_3$$

a_1', a_2', a_3'
b_1', b_2', b_3'
c_1', c_2', c_3'
d_1', d_2', d_3'

Sets of non-dimensional coefficients used in the propulsion equation above. The set which will be in effect at any time during a simulated maneuver will depend on the value of n' and the numbers k_1, k_2, k_3.

NOMENCLATURE

All symbols used in the equations of motion and in the auxiliary equations and relationships which appear in this report are defined below. Any dimensions involved will be consistent with the foot-pound-second system of units. All angles are in degrees. The Fortran variables corresponding to these symbols are shown in Appendix B .

SYMBOL	DEFINITION
$\dot{}$	A dot over any symbol signifies differentiation with respect to time.
B	Buoyancy force which is positive upwards.
m	Mass of the submarine including the water in the free flooding spaces.
ℓ	Overall length of the submarine
U	Linear velocity of origin of body axes relative to an earth-fixed axis system.
u	Component of U along the body x-axis.
v	Component of U along the body y-axis.
w	Component of U along the body z-axis.

u_c	Command speed: A steady value of u for a given propeller rpm when α, β and control surface angles are zero. Sign changes with propeller reversal.
x	Longitudinal axis of the body fixed coordinate axis system.
y	Transverse axis of the body fixed coordinate axis system.
z	Vertical axis of the body fixed coordinate axis system.
x_o	Distance along the x_o axis of an earth-fixed axis system.
y_o	Distance along the y_o axis of an earth-fixed axis system.
z_o	Distance along the z_o axis of an earth-fixed axis system.
p	Component of angular velocity about the body fixed x-axis.
q	Component of angular velocity about the body fixed y-axis.
r	Component of angular velocity about the body fixed z-axis.
z_B	The z coordinate of the center of buoyance (CB) of the submarine.

α	Angle of attack.
β	Angle of drift.
δb, D_b	Deflection of bowplane (or sailplane)
δr, D_r	Deflection of rudder.
δs, D_s	Deflection of sternplane.
n'	The ratio u_c/u.
θ	Pitch angle.
Ψ	Yaw angle.
ϕ	Roll angle.
ρ	Mass density of sea water.
W_i	Weight of water blown from a particular ballast tank identified by the integer assigned to the index i.
ω	Angular velocity.
t	Time.
x_{ti}	Location along the body x-axis of the center of mass of the i^{th} ballast tank when this tank is filled with sea water.

$(F_x)_p$	Propulsion force (see auxiliary equations and relationships).
I_x	Moment of inertia of a submarine about the x-axis.
I_y	Moment of inertia of a submarine about the y-axis.
I_z	Moment of inertia of a submarine about the z-axis.
$K_{\dot{p}}'$, K_p', $K_{p\|p\|}'$, K_{qr}', K_r', $K_{\dot{r}}'$, $K_{\dot{v}}'$, K_{wp}', K_*', K_v', $K_{v\|v\|}'$, K_{vw}', $K_{\delta r}'$	Non-dimensional constants each of which is assigned to a particular force term in the equation of motion about the body x-axis.
$M_{\dot{q}}'$, M_{rr}', M_{rp}', $\Delta M_{rp}'$, M_q', $M_{\|q\|\delta s}'$, $M_{\|w\|q}'$, $M_{\dot{w}}'$, M_{vr}', M_{vp}', M_{qn}', M_*', M_w', $M_{w\|w\|}'$, $M_{\|w\|}'$, M_{ww}', M_{vv}', $M_{\delta s}'$, $M_{\delta b}'$, M_{wn}', $M_{w\|w\|n}'$, $M_{\delta sn}'$	Non-dimensional constants each of which is assigned to a particular force term in the equation of motion about the body y-axis.

$N_{\dot{r}}'$, N_{pq}', $N_{\dot{p}}'$, N_r', $N_{|r|\delta r}'$, $N_{|v|r}'$,
N_p', $N_{\dot{v}}'$, N_{wp}', N_{rn}', N_*', N_v',
$N_{v|v|}'$, $N_{\delta r}'$, $N_{\delta rn}'$, N_{vn}', $N_{v|v|n}'$,
N_{wv}'

Non-dimensional constants each of which is assigned to a particular force term in the equation of motion about the body z-axis.

X_{qq}', X_{rr}', X_{rp}', $X_{\dot{u}}'$, X_{vr}', X_{wq}',
X_{uu}', X_{vv}', X_{ww}', $X_{\delta r\delta r}'$, $X_{\delta s\delta s}'$,
$X_{\delta b\delta b}'$, X_{vvn}', X_{wwn}', $X_{\delta s\delta sn}'$,
$X_{\delta r\delta rn}'$

Non-dimensional constants each of which is assigned to a particular force term in the equation of motion along the body x-axis.

$Y_{\dot{r}}'$, $Y_{\dot{p}}'$, Y_{pq}', $Y_{p|p|}$, $Y_{\dot{v}}'$, Y_{wp}',
$Y_{v|r|}'$, Y_r', $Y_{|r|\delta r}'$, Y_p', Y_{rn}',
Y_*', Y_v', $Y_{v|v|}'$, $Y_{\delta r}'$, $Y_{\delta rn}'$,
Y_{vn}', $Y_{v|v|n}'$, $\bar{Y}_{wv}'$, $(F_y)_{vs}$

Non-dimensional constants each of which is assigned to a particular force term in the equatio of motion along the body y-axis

$Z_{\dot{q}}'$, Z_{rr}', Z_{rp}', $Z_{\dot{w}}'$, Z_{vr}, Z_{vp}',
$\Delta Z_{vp}'$, Z_q', $Z_{|q|\delta s}$, $Z_{w|q|}'$,
Z_{qn}', Z_*', Z_w', $Z_{w|w|}'$, $Z_{|w|}'$,
Z_{vw}', Z_{vv}', $Z_{\delta s}'$, $Z_{\delta b}'$, Z_{wn}',
$Z_{w|w|n}'$, $Z_{\delta sn}'$, $(F_z)_{vs}$

Non-dimensional constants each of which is assigned to a particular force term in the equatio of motion along the body z-axis

APPENDIX B

```
*   ROLL CONTROL PROGRAM
*   THE DEPTH CONTROLLER GAINS WAS CALCULATED FOR 15 KNOTS BASE SPEED
*   THESE GAINS ARE VALID ONLY FOR THE ASSOCIATED HYDRODYNAMIC COEFFICIENTS
*  TRIM TANKS NOT EMPLOYED---TANK LEVELS AT,FT,AND AU SET TO ZERO
*   DF REPRESENTS THE FAIRWATER PLANE DEFLECTION IN DIFFERANTIALLY DEFLECTED
*   MODE
*   PARAMETERS ARE ASSIGNED AS FOLLOWS
* MAX PLANE RATE---PLRT
INTGER I,J,NFLCT
D      COMMON AINV(6,6)
PARAM I=0,J=0,K=0
*    ORDERED SPEED
PARAM UCK=24.
*      ORDERED DEPTH
PARAM ZODR = 0.0
*    ORDERED RUDDER
PARAM ORDRUD=35.
*
*     SSN DATA
*
PARAM ZDF=0.0015517
*
PARAM LC=251.75,ML=0.0161735
PARAM A1=-0.1766E-02,A2=-0.1403E-02,A3=0.3169E-02
PARAM IX=2.634865E-05,IY=8.285997E-04,IZ=8.285997E-04
PARAM XUDOT=-0.4840E-03,XVR=0.1818E-01,XWQ=-0.1474E-01,XVV=0.1733E-01
PARAM XDRDR=-0.512E-02,XDSDS=-0.288E-02,XDBDB=-0.347E-02,XQQ=-0.517E-03
PARAM XRR=0.185E-03,XPP=0.3885E-03,XWW=0.
PARAM YVDOT=-0.1818E-01,YWP=0.01474,YV=-0.05547,Y1V1V=-0.0928,YR=0.00138
PARAM YV1R1=-0.0119,YP=-0.00213,YRDOT=-0.000185,YPDOT=-0.0003885
PARAM YDR=0.01218,YPQ=0.000517,YWV=-0.1297
PARAM ZWDOT=-0.01474,ZVP=-0.01818,ZS =   -0.1E-04,ZW=-0.02342
PARAM Z1W1=-0.06003,ZVV=0.1297,ZQ=-0.00962,Z1Q1=-0.0119,ZVR=-0.01951
PARAM ZFR=-0.002617,ZDS=-0.01134,ZDB=-0.00558,ZQDOT=-0.000517
PARAM Z1W1=-0.001253,ZWW=0.0004514,ZRP=-0.002471,BDZVP=0.01147
PARAM KPDOT=-0.313E-04,KQR=0.36E-04,KRDOT=-0.358E-04,K1P1P=-0.17E-04
PARAM KV=-0.0044546,K1V1V=-0.003998,KP=-0.000162,KR=-0.00073173,KS=0.
PARAM KVDOT=-0.000315,KVW=0.00291,KDF=0.496E-04,KWP=0.3885E-03
PARAM MQDOT=-0.000787,MRP=0.00072,MS =   0.001418,MW=0.004757
PARAM M1W1W=-0.01104,MVV=0.03061,MQ=-0.0055,M1W1Q=-0.00553,MVR=-0.009073
PARAM MRR=-0.001,MWDOT=-0.000584,MDS=-0.00532,MDB=0.001137
PARAM M1W1=-0.007886,MWW=0.002095,MVP=0.002471,BDMRP=-0.000944
PARAM NRDOT=-0.000751,NPQ=-0.000787,NPDOT=-0.0000358,NV=-0.01483
PARAM N1V1V=0.01635,NR=-0.004917,N1V1R=-0.00553,NP=-0.000377
PARAM NVDOT=-0.000141,NDR=-0.00567,NWV=0.03061,NWP=-0.000517
PARAM BZB=0.0032893
PARAM FLRT=.1222
INTEG RKSFX
```

```
INTGER NPLOT
PARAM NPLOT = 1
INCON FT=0.,AT=0.,AU=0.
CONTRL FINTIM=140.,DELS=0.1,DELT=0.01
INITIAL
      MS = 0.
      ZS = 0.
      KS=0.0
      DS=1.
      DSCOM=0.
      DFCOM=0.
      DB=0.
      DF=0.
      DR=0
      RUDORD=0.
       K1=3
      K2=10
      KGA=1
      PDOT=0.
      PIDOT=0.
      YADOT=0.
      ZDDOT=0.0
      UDOT=0.
      VDOT=0.
      WDOT=0.
      PDOT=0.
      QDOT=0.
      RDOT=0.
      DSA=0.0
      DSC=0.
      DST=0.
      DFA=0.
      DFC=0.
      DFT=0.
      ZVP=ZVP+DDZVP
      MRP=MRP+DEMRP
      DO 2 I=1,6
      DO 2 J=1,6
2     AINV(I,J)=0.0
      AINV(1,1)=60.3956
      AINV(2,2)=30.1071
      AINV(2,4)=-52489.43
      AINV(2,6)=272.435
      AINV(3,3)=32.6514
      AINV(3,5)=-2630.43
      AINV(4,2)=-0.671957
      AINV(4,4)=18574.5
      AINV(4,6)=-401.159
```

```
      AINV(5,3)=-.0468826
      AINV(5,5)=632.743
      AINV(6,2)=0.00419939
      AINV(6,4)=-402.361
      AINV(6,6)=642.067
      UC = UCK * 1.68889
      UK=UCK
      LC2=LC**2
      LC2=LC**2
      LC3=LC2*LC
      IZX=IZ-IX
      IYX=IY-IX
      IZY=IZ-IY
DYNAMIC
      UK=U/1.68889
      MINDEP=-DEPTH
      IF(TIME.GT.20.AND.TIME.LT.80) RUDORD=35
      IF(TIME.GT.30) RUDORD=0.0
      RUDORD=LIMIT(-35.0,35.0,RUDORD)
      RUDRAD=RUDORD/57.296
      RUDERR=RUDRAD-DR
      RUDERR=LIMIT(-0.087266,0.087266,RUDERR)
      DRA = DR * 57.296
*   ROLL CONTROLLER
      ROLLER=ROLL
      ROLLER=LIMIT(-0.087266,+0.087266,ROLLER)
      DFCO=-K1*ROLLER-K2*P
      MINDRA = -DRA
      PITGRA=PITCH*57.296
      PDTGRA = PIDOT * 57.296
      ROLGRA=ROLL*57.296
      YAWGRA=YAW*57.296
      YDTGRA=YADOT * 57.296
      BETA=(V/U)*57.296
      DSGRA=DS*57.296
      DFGRA=DF*57.296
*     DEPTH CONTROL GAINS
      F1=-0.31623
      F2=-26.88/UK
      F3=36.069
      F4=1533.45/UK
* AUXILIARY EQUATIONS
      RODOT=R+YADOT*SIN(PITCH)
      PIDOT=(Q-YADOT*COS(PITCH)*SIN(ROLL))/COS(ROLL)
      YADOT=(R+PIDOT*SIN(ROLL))/(COS(PITCH)*COS(ROLL))
      ZODOT=-U*SIN(PITCH)+V*COS(PITCH)*SIN(ROLL)...
      +W*COS(PITCH)*COS(ROLL)
      PA1=XDRDR*U*U*DR*DR/LC
```

```
      PA2=XDSDS*L*U*DS*DS/LC
      PA3=XDBDB*U*U*LB*DB/LC
      PB1=YDR*L*U*DR/LC
      PC2=ZDS*L*U*DS/LC
      PC3=ZDB*U*U*DB/LC
      PD1=KDR*L*L*DR/LC2
      PE2=MDS*U*U*DS/LC2
      PE3=MDB*L*U*DB/LC2
      PF1=NDR*U*U*DR/LC2
      PA=PA1+PA2+PA3
      PB=PB1
      PC=PC2+PC3
      PD=PD1
      PE=PE2+PE3
      PF=PF1
*NON LINEAR RELATIONS
      ABV=ABS(V)
      ABW=ABS(W)
      ABP=ABS(P)
      ABQ=ABS(Q)
      ABR=ABS(R)
      VVWW=V*V+W*W
      AVW=SQRT(VVWW)
      ABWP=FCNSW(W,-1.0,0.0,1.0)
      ABVP=FCNSW(V,-1.0,0.0,1.0)
      SA1=+LC*(XQQ*Q**2+XRR*R**2+XRP*R*P)
      SA2=+(ML*V*R+XVR*V*R+XWQ*W*Q-ML*W*Q)
      SA3=+(XVV*V**2+XWW*W**2)/LC-SIN(PITCH)*(AT+FT+AU)
      SA4=+(A1*U**2+A2*U*UC+A3*UC**2)/LC
      SB1=+LC*YPQ*P*Q
      SB2=+(YWP*W*P+YV1R1*ABR*AVW*ABVP+ML*W*P-ML*U*R)
      SB3=+(YWV*W*V+Y1V1V*AVW*V)/LC+SIN(ROLL)*COS(PITCH)...
      *(AT+FT+AU)
      SB4=(YR*R+YP*P+YV*V/LC)*U
      SC1=LC*R*(ZRR*R+ZRP*P)
      SC2=+(ZVP*V*P+ZVR*V*R+ZW1Q1*ABQ*AVW*ABWP+ML*L*Q-ML*P*V)
      SC3=+(ZWW*W**2+ZVV*V**2+ZW1W1*W*AVW+U*Z1W1*ABW+U*U*ZS)/LC
      SC4=ZQ*U*Q+ZW*U*W/LC+COS(PITCH)*COS(ROLL)*(AT+FT+AU)
      SD1=+(KQR*Q*R+K1P1P*ABP*P)-IZY*Q*R
      SD2=(KWP*W*P-BZB*SIN(ROLL)*COS(PITCH))/LC
      SD3=+(K1V1V*V*AVW+KVW*V*W+KS*U**2)/LC2
      SD4=((KP*P+KR*R)/LC+KV*V/LC2)*U
      SE1=(MRP*P+MRR*R+IZX*P)*R
      SE2=((MVR*R+MVP*P)*V+M1W1Q*AVW*Q-BZB*SIN(PITCH))/LC
      SE3=(MVV*V**2+MWW*W**2+M1W1W*AVW*W+M1W1*U*AVW+U**2*MS)/LC2
      SE4=MQ*U*Q/LC+(MW*U*W-(175.5*FT-219.5*AT)*COS(PITCH)...
      *COS(ROLL))/LC2
      SF1=(NPQ-IYX)*P*Q
```

```
      SF2=+(NWP*W*P+N1V1R*AVW*R)/LC
      SF3=(NWV*W+N1V1V*AVW)*V/LC2
      SF4=(NP*P+NR*R)*U/LC+(NV*U*V+(175.5*FT-219.5*AT)*...
      COS(PITCH)*SIN(ROLL))/LC2
      SA=SA1+SA2+SA3+SA4
      SB=SB1+SB2+SB3+SB4
      SC=SC1+SC2+SC3+SC4
      SD=SD1+SD2+SD3+SD4
      SE=SE1+SE2+SE3+SE4
      SF=SF1+SF2+SF3+SF4
      ZA=SA+FA
      ZB=SB+FB
      ZC=SC+FC
      ZD=SD+FD+ZDE*U*U*DE/LC2+DISTUR/(LC3*LC2)
      ZE=SE+FE
      ZF=SF+FF
*   EQUATIONS OF MOTION
      UDOT=AINV(1,1)*ZA+AINV(1,2)*ZB+AINV(1,3)*ZC+AINV(1,4)*ZD+...
      AINV(1,5)*ZE+AINV(1,6)*ZF
      VDOT=AINV(2,1)*ZA+AINV(2,2)*ZB+AINV(2,3)*ZC+AINV(2,4)*ZD+...
      AINV(2,5)*ZE+AINV(2,6)*ZF
      WDOT=AINV(3,1)*ZA+AINV(3,2)*ZB+AINV(3,3)*ZC+AINV(3,4)*ZD+...
      AINV(3,5)*ZE+AINV(3,6)*ZF
      PDOT=AINV(4,1)*ZA+AINV(4,2)*ZB+AINV(4,3)*ZC+AINV(4,4)*ZD+...
      AINV(4,5)*ZE+AINV(4,6)*ZF
      QDOT=AINV(5,1)*ZA+AINV(5,2)*ZB+AINV(5,3)*ZC+AINV(5,4)*ZD+...
      AINV(5,5)*ZE+AINV(5,6)*ZF
      RDOT=AINV(6,1)*ZA+AINV(6,2)*ZB+AINV(6,3)*ZC+AINV(6,4)*ZD+...
      AINV(6,5)*ZE+AINV(6,6)*ZF
DERIVATIVE
NOSORT
      DR=INTGRL(0.0,KGN*RUDERR)
      U = INTGRL(UO,UDOT)
      V=INTGRL(0.,VDOT)
      W=INTGRL(0.,WDOT)
      P=INTGRL(0.,PDOT)
      Q=INTGRL(0.,QDOT)
      R=INTGRL(0.,RDOT)
      DEPTH=INTGRL(0.0,ZODOT)
      ROLL=INTGRL(0.0,RODOT)
      PITCH=INTGRL(0.0,PIDOT)
      YAW=INTGRL(0.0,YADOT)
*     AUTOMATIC CONTROLLER FOR STERN PLANE ONLY
      ZOER=DEPTH-ZODR
      PERR=PITCH-PORD
      ZOER=LIMIT(-20.,+20.,ZOER)
      PERR=LIMIT(-0.087266,+0.087266,PERR)
      DSAD=F1*ZOER+F2*ZODOT+F3*PERR+F4*PIDOT
```

```
      IF (DSAC.GT.0.61086) DSAC=0.61086
      IF (DSAC.LT.-0.61086) DSAD=-0.61086
      DSCD=RSALFL(0.0,.1,DSAD)
* PLANE ANGLE GENERATOR
      DSER=DSCD-DS
      DFER=DFCD-DF
      IF(DFER.EQ.0.0) GO TO 12
      IF(DFER.LT.0.0) GO TO 17
      IF(DFTMP.EQ.1) GO TO 18
      DFTMN=0
      DFTMP=1
      DFC=DF
      DFT=TIME
   18 DFA=(TIME-DFT)*PLRT
      DF=DFC+DFA
      GO TO 11
   17 IF(DFTMN.EQ.1) GO TO 19
      DFTMP=0
      DFTMN=1
      DFC=DF
      DFT=TIME
   19 DFA=(DFT-TIME)*PLRT
      DF=DFC+DFA
      GO TO 11
   12 DFTMN=0
      DFTMP=0
   11 CONTINUE
      IF(DSER.EQ.0.0) GOTO 22
      IF(DSER.LT.0.0) GOTO 27
      IF(DSTMP.EQ.1) GOTO 28
      DSTMN=0
      DSTMP=1
      DSC=DS
      DST=TIME
   28 DSA=(TIME-DST)*PLRT
      DS=DSC+DSA
      GOTO 21
   27 IF(DSTMN.EQ.1) GOTO 29
      DSTMP=0
      DSTMN=1
      DSC=DS
      DST=TIME
   29 DSA=(DST-TIME)*PLRT
      DS=DSC+DSA
      GOTO 21
   22 DSTMN=0
      DSTMP=0
   21 CONTINUE
```

```
SAMPLE
      CALL DRWG(1,1,TIME,DEPTH)
      CALL DRWG(1,2,TIME,DRA)
      CALL DRWG(2,1,TIME,PITGRA)
      CALL DRWG(2,2,TIME,DRA)
      CALL DRWG(3,1,TIME,ROLGRA)
      CALL DRWG(3,2,TIME,DRA)
      CALL DRWG(4,1,TIME,DSGRA)
      CALL DRWG(4,2,TIME,DRA)
      CALL DRWG(5,1,TIME,DFGRA)
      CALL DRWG(5,2,TIME,DRA)
TERMINAL
PRINT 1.,UK,PITGRA,DEPTH,YAWGRA,ROLGRA,DSGRA,DFGRA,DRA,DISTUR
      CALL ENDRW(NPLOT)
END
STOP
//PLOT.SYSIN DD *
K1=3 K2=10 CRDRUD=35 UCK=24
DEPTH VS TIME                                                   4
                                   5.0       7.0
K1=3 K2=10 CRDRUD=35 UCK=24
PITCH VS TIME                                                   4
                                   5.0       7.0
K1=3 K2=10 CRDRUD=35 UCK=24
ROLL VS TIME                                                    4
                                   5.0       7.0
K1=3 K2=10 CRDRUD=35 UCK=24
STERN PLANE VS TIME                                             4
                                   5.0       7.0
K1=3 K2=10 CRDRUD=35 UCK=24
SAILPLANE VS TIME                                               4
                                   5.0       7.0
```

LIST OF REFERENCES

1. Donald, J.L. An Investigation Of Snap Roll In Submarines, Master's Thesis, Massachusetts Institute Of Technology, 1977.

2. Stamps, D.W., Control Of Roll In A Turning Submarine, Master's Thesis, Naval Postgraduate School, 1977.

3. David W. Taylor Naval Ship Research And Development Center Report SPD-632-10, A Method Of Estimating The Sway Force And Rolling Moment On A Submarine Due To Differentially Deflected Sailplanes, by Keith P. Kerney, November 1975.

4. Naval Ship Systems Command, Fundamentals Of Submarine Hydrodynamics, Motion And Control, NAVSHIPS 0911-003-6010 by General Dynamics/Electric Boat Division, 1971.

5. Naval Ship Research And Development Center Report No. 2510, Standard Equations Of Motion For Submarines Simulation, by Morton Gertler and Grant R. Hagen, June 1967.

6. Naval Ship Research And Development Center Report No. P-433-H-01, Users Guide NSRDC Digital Program For Simulating Submarine Motion 22MN Revision - 1.0, Ronald W. Richard, June 1971.

7. Drurey, H.L., Automatic Control Of Submarine Depth, Pitch And Trim, Master's Thesis, Naval Postgraduate School, 1975.

8. Kirk, D.E., Optimal Control Theory, Prentice-Hall Inc., 1970.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0142 Naval Postgraduate School Monterey, California 93940	2
3.	Department Chairman, Code 62 Department Of Electrical Engineering Naval Postgraduate School Monterey, California 93940	2
4.	Dr. G.J. Thaler, Code 62Tr Department Of Electrical Engineering Naval Postgraduate School Monterey, California 93940	5
5.	Prof. A. Gerba, Code 62 Gz Department Of Electrical Engineering Naval Postgraduate School Monterey, California 93940	1
6.	Deniz Kuvvetleri Komutanligi Egitim Dairasi Ankara - Turkey	1
7.	Istanbul Teknik Universitasi Elektrik Falcultesi Gümussuyu Istanbul - Turkey	1
8.	Bogazici Universitesi P.K. 2 Bebek, Istanbul - Turkey	1
9.	Orto Dogu Teknik Universitesi Ankara - Turkey	1
10.	Yzb. Izzet Artunc Nüzhetiye Karokol Sokak Arzu AP=20/2 Besiktas/ Istanbul - Turkey	2